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FLYWHEEL DRIVE SYSTEMS STUDY

R. R. Gilbert, et al

Lockheed Missiles and Space Company

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FLYWHEEL DRIVE SYSTEMS STUDY

FINAL REPORT

CONTRACT NO. 68-04-0048

TO

ENVIRONMENTAL PROTECTION AGENCY

OFFICE OF AIR PROGRAMS

ADVANCED AUTOMOTIVE POWER SYSTEMS
DEVELOPMENT DIVISION

BY

R. R. GILBERT, G. E. HEUER, E. H. JACOBSEN,
E. B. KUHNS, L. J. LAWSON AND W. T. WADA

GROUND VEHICLES SYSTEMS
LOCKHEED MISSILES AND SPACE COMPANY, INC.
SUNNYVALE, CALIFORNIA

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This systems study effort has been directed toward the verification and refinement of the conclusions reached in a previous study, which indicated that the fly wheel hybrid drive concept might be a technically feasible way to power a full size automobile. The present study makes use of more detailed input information on engine emissions on transmission characteristics. These data are augmented by detailed flywheel technology studies and test results to provide the background for more precise conclusions regarding the flywheel drive concept. The results indicate that the flywheel hybrid drive concept is a technically feasible propulsion system for a full size automobile. The report describes the work done to accomplish the following goals: advance the development of flywheel systems technology including the development of final designs on conformal housings, bearings, seals, and evacuation systems; demonstrate positive flywheel energy containment in burst tests of flywheels; formulate safety analyses, using fault-tree and gross-hazard methodologies, produce engine-mapping project data to permit calculation of engine emission data resulting from flywheel drive operations over the Urban Dynomometer Driving Schedule. Provide systems coordination in the areas of flywheel assembly designs, interfaces configuration tradeoffs, speed selections, cost, and predicted dyno cycle performance.

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SUMMARY

The Flywheel Drive Systems Study effort has been directed toward the verification and refinement of the conclusions reached in the Flywheel Feasibility Study and Demonstration (Contract No. EHS 70-104). This previous study indicated that the flywheel hybrid drive concept might be a technically feasible way to power a full size automobile. The present study makes use of more detailed input information on engine emissions supplied by the U. S. Bureau of Mines, Petroleum Research Center, and on transmission characteristics supplied by transmission contractors. These data are augmented by detailed flywheel technology studies and test results to provide the background for more precise conclusions regarding the flywheel drive concept.

RESULTS AND CONCLUSIONS

The flywheel hybrid drive concept is a technically feasible propulsion system for a full size automobile.

A theoretical computer analysis of predicted emissions from the flywheel drive system, contrasted with emissions theoretically predicted for a conventional three-speed automatic transmission drive, indicates some theoretical emission reduction. This comparison was made with a flywheel hybrid drive assumed to have an oxidation catalyst and exhaust gas recirculation (a NO_x catalyst was not assumed). The conventional system was assumed to have the same emission controls. The cold start effect was not included. The emission predictions indicated that the emission levels attainable by the flywheel hybrid system were not low enough to comply with the 1976 requirements.

The projected production cost of complete family car flywheel assemblies is $100, plus or minus $15, depending on flywheel configuration; this is within previous estimates. (Ref. 1).

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Additional engine emission data are required to permit an accurate evaluation of the flywheel drive as a cost-effective means of emission reduction for the family car.

Plastic growth of steel flywheels can provide a lightweight means of overspeed failure control.

Flywheel burst containment can be achieved through use of relatively heavy, homogeneous metal rings or composite (filamentary) containment structures.

The flywheel drive may provide safe family car propulsion if care is taken in systems and component design.

All elements of a practical family car flywheel assembly are now available without further technology development.

The cost of ownership, size, and weight of a family car flywheel drive fall within the established EPA/OAP Vehicle Design Goals.

RECOMMENDATIONS

Further engine emission measurements should be made with dynamometer simulation of engine loads over the dynamometer driving cycle for a conventional automatic transmission and for various configurations of the flywheel transmission so as to provide an accurate determination of emission reductions.

Additional design and testing should be conducted to effect further improvement of flywheel burst-containment structures.

Development of flywheel drive transmissions should be postponed until more definitive results of the emission reduction potentials of the flywheel drive are obtained.

Section 1
INTRODUCTION

BACKGROUND

The Advanced Automotive Power Systems (AAPS) program being conducted by the Environmental Protection Agency/Office of Air Programs (EPA/OAP) has the stated goal of producing an automobile with an unconventional propulsion system with emissions meeting the standards of the Clean Air Act of 1970 while remaining competitive with conventional vehicle power systems. The candidate propulsion systems considered in this program include heat engine systems, electric systems, and hybrid systems in which category the flywheel drive was classified. The flywheel drive as considered in the AAPS program could be incorporated in a configuration in which a heat engine operated in a restrained mode provides the average level of energy required for vehicle operation while a relatively small flywheel supplies the power peaks for acceleration. One basic configuration considered for such a heat-engine/flywheel drive is shown in Fig. 1-1. This flywheel drive configuration with a bilateral transmission reduces engine emissions by permitting recuperation of vehicle kinetic energy when braking or decelerating as well as by reducing engine transients during vehicle operations. In addition, the use of the flywheel for the provision of vehicle acceleration power can reduce the installed engine horsepower to less than that now required for the desired performance of a full-size family car, as specified by the EPA Vehicle Design Goals. (See Appendix A.)

FLYWHEEL FEASIBILITY STUDY AND DEMONSTRATION

The general feasibility of the flywheel drive for reduced emission vehicles was indicated in the Flywheel Feasibility Study and Demonstration (Contract No. EHS 70-104) conducted for EPA/OAP by Lockheed Missiles & Space Company, Inc. (LMSC), as reported in Ref. 1-1. Although the results of this study showed the pure flywheel configuration to be a possible candidate for intra-city buses, the only possible con-

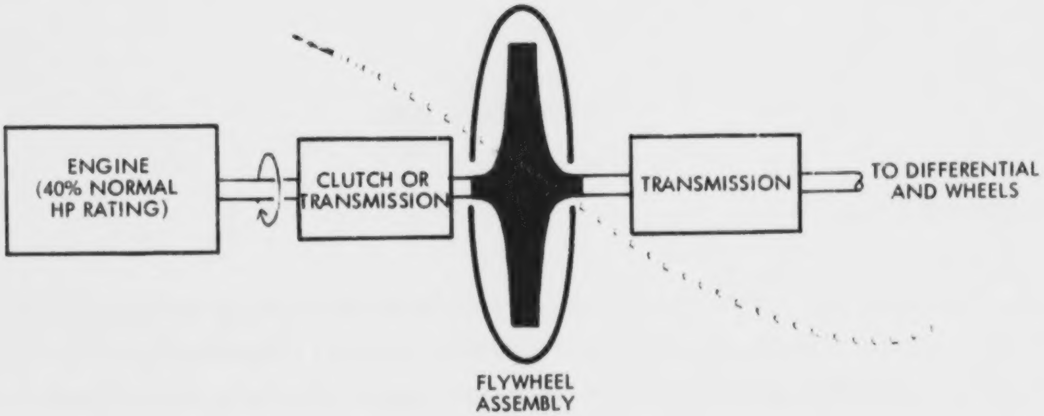


Fig. 1-1 Series-Type Flywheel Drive System

figuration for family cars is the combination heat engine-flywheel system. Conceptual layouts of the flywheel drive installed in a family car are shown in Fig. 1-2 (conventionally mounted flywheel and transmission) and in Fig. 1-3 (transaxle-mounted flywheel and transmission).

The following recommendations were made to EPA /OAP by LMSC at the completion of the Flywheel Feasibility Study and Demonstration:

- Development activities on flywheel drive vehicles should be continued.
- Emission sampling tests should be conducted on candidate heat engines operated under steady-state conditions.
- Transmission and control system studies should be initiated.
- Flywheel technology development and testing should be continued in the areas of failure control, ancillary selection, and configuration tradeoffs.

FLYWHEEL DRIVE SYSTEMS STUDY

The conclusions and recommendations of the prior Flywheel Feasibility Study were utilized by EPA /OAP to structure a comprehensive program aimed at future study of the flywheel drive when specifically applied to the family car.

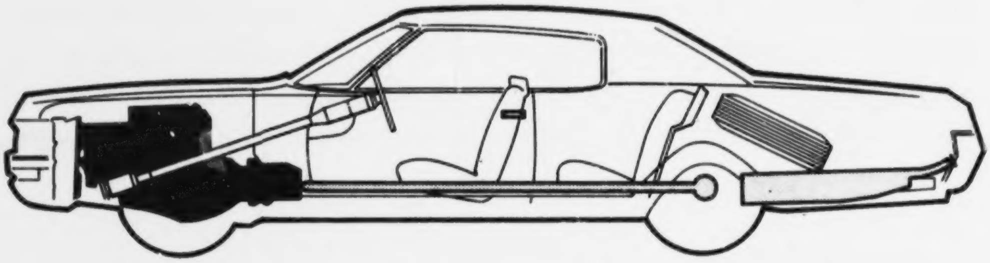


Fig. 1-2 Drivetrain Arrangement for Engine-Mounted Flywheel/ Transmission

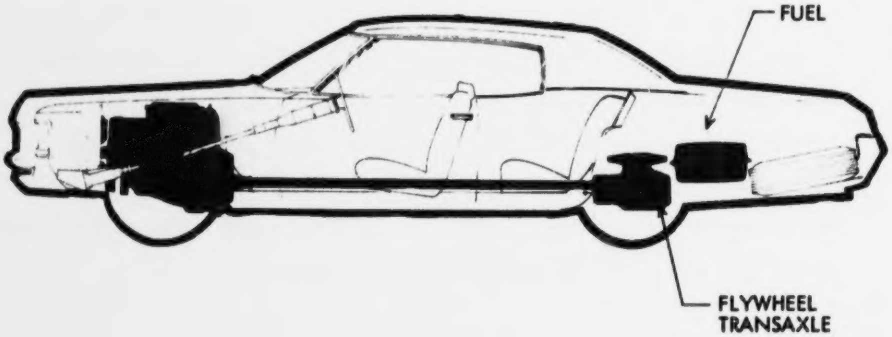

FUEL
FLYWHEEL
TRANSAXLE

Fig. 1-3 Drivetrain Arrangement for Transaxle Flywheel/Transmission

The present EPA/OAP Program combines the efforts of four organizations, under coordination by that agency to accomplish a highly objective, quantitative assessment of the practicality of a flywheel drive system for a full-size, full-performance, family car. The task of emission mapping of spark-ignition gasoline engines was assigned to the U. S. Bureau of Mines Petroleum Research Center (PRC) (Bartlesville, Oklahoma). Two parallel contracts for the analysis of transmission feasibility, controls, performance, and cost were awarded to Mechanical Technology, Inc. (MTI) and Sundstrand Aviation, division of Sundstrand Corporation. The fourth contract was awarded to LMSC to conduct the Flywheel Drive System Study (EPA Contract No. 68-04-0048).

STUDY OBJECTIVES

The Flywheel Drive Systems Study program was structured under the direction of EPA/OAP to accomplish the following overall goals:

- Advance the development of flywheel systems technology, including the development of final designs on conformal housings, bearings, seals, and evacuation systems.
- Demonstrate positive flywheel energy containment in burst tests of flywheels.
- Formulate safety analyses, using fault-tree and gross-hazard methodologies.
- Produce engine-mapping project data received from PRC to permit calculation of engine emission data resulting from flywheel drive vehicle operations over the Urban Dynamometer Driving Schedule (dyno cycle). This is the so-called LA-4 schedule used in the 1972 Federal Test Procedure.
- Provide to MTI and Sundstrand systems coordination in the areas of flywheel assembly designs, interfaces, configuration tradeoffs, speed selections, cost, and predicted dyno cycle performance.

Section 2

DRIVE SYSTEM REQUIREMENTS

In order to provide a realistic and common basis for design to the transmission contractors, drive system requirements were established early in the program.

ENGINE CHARACTERISTICS

Because of a lack of data on engine emissions, the EPA directed that minimization of brake specific fuel consumption (bsfc) be used as a substitute criterion. A bsfc map for a medium-size V-8 engine (Fig. 2-1) was supplied by EPA to be used as a standard reference. Accessory loads for this engine were stipulated by the EPA, as shown in Fig. 2-2.

REFERENCE CONVENTIONAL TRANSMISSION

The EPA provided characteristic data in graphic form (see Appendix B) for a conventional automatic transmission to be used as a comparative reference for candidate flywheel transmission designs.

FLYWHEEL TRANSMISSION PERFORMANCE SPECIFICATION

A transmission performance specification was prepared in order to translate the vehicle performance requirements of the vehicle design goals (Appendix A), stipulated by the EPA as a design basis, into transmission performance requirements. Average values of vehicle weight were assumed, namely, a test weight Wt = 4,300 lb and a gross weight Wg = 5,000 lb.

The various performance requirements presented in Appendix A are shown in Fig. 2-3. Paragraph 8f of Appendix A stipulates a 30-percent grade as the maximum on which the

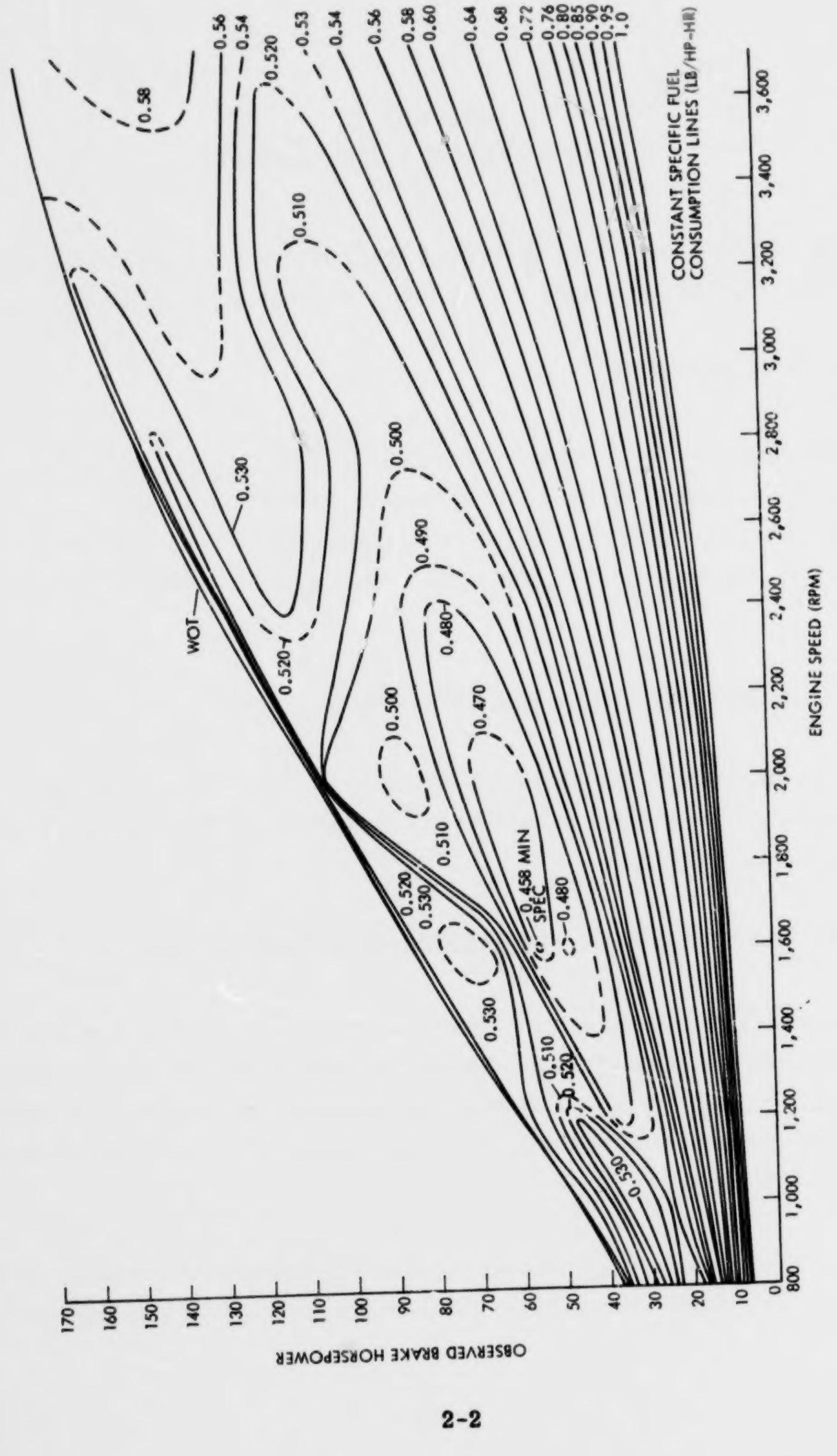
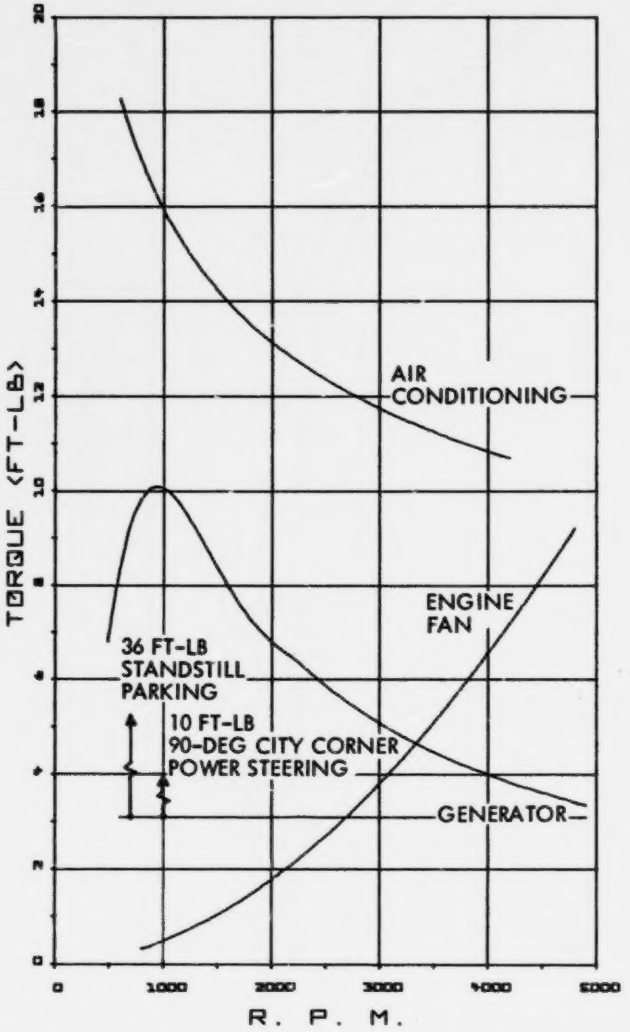


Fig. 2-1 Brake Specific Fuel Consumption Map – Medium-Size V-8 Engine



AIR CONDITIONING

$600 \leq X \leq 4{,}200$

$Y = AX^B$

$A = 106.633601$

$B = -0.275741$

GENERATOR

$490 \leq X \leq 2{,}200$

$Y = F+AX+BX^2+CX^3+DX^4+EX^5$

$F = -12.322974$

$A = 6.6444128E-2$

$B = -7.0475694E-5$

$C = 3.2954301E-8$

$D = -7.1021053E-12$

$E = 5.6619139E-16$

$2{,}200 \leq X \leq 4{,}900$

$Y = \dfrac{1}{A + BX}$

$A = 0.038335$

$B = 0.000053$

ENGINE FAN

$Y = AX^B$

$A = 10.9199E-7$

$B = 18.8149E-1$

The above equations were determined by computer curve-fitting data supplied by the EPA. (X = rpm and Y = torque in ft-lb.) The curves to the left are computer plots of these equations.

Fig. 2-2 Accessory Loads for Typical Medium-Size V-8 Engine

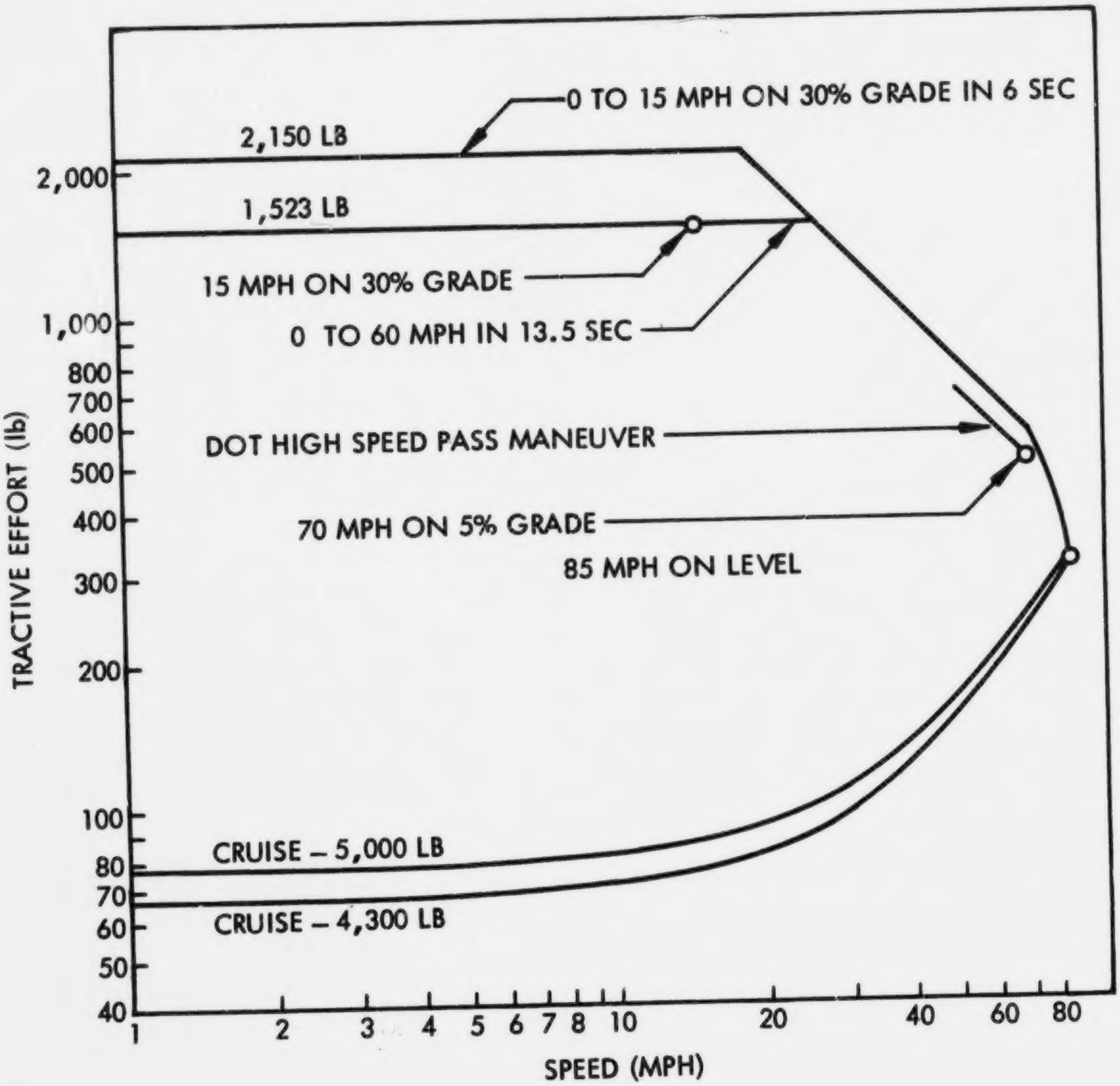


Fig. 2-3 Minimum Tractive Effort Vs. Speed Requirements for Flywheel Drive System (First Quadrant Only)

vehicle is required to operate, so the tractive effort of 1,523 lb for operation on a 30-percent grade at 15 mph could be used as the maximum tractive effort required.

The acceleration from 25 to 70 mph in 15 sec (para. 8d of Appendix A), when run at constant horsepower, requires 107 hp from 26 to 70 mph (25 to 26 mph being at the tractive effort limit of 1,523 lb previously established).

The requirement for 0 to 60 mph in 13.5 sec (para. 8c of Appendix A) requires 106 hp at constant horsepower, with the tractive effort limit of 1,523 lb to 26 mph, and thus just misses being a determining factor. The high speed pass maneuver of the U.S. Department of Transportation (DOT) (para. 8e of Appendix A) and the 70-mph, 5-percent grade requirements (para. 8f of Appendix A) fall farther below the 107-hp line. The maximum speed of 85 mph on the level requires a tractive effort of 312 lb.

Between speeds of 70 and 85 mph, a linear interpolation was employed so that the power available for acceleration fades gradually to zero as the maximum cruise speed of 85 mph is approached.

The vehicle performance requirements of Appendix A are thus met by a tractive effort of 1,523 lb from 0 to 26 mph, a constant power of 107 hp from 26 to 70 mph, and a linear taper in power from 107 hp at 70 mph to a tractive effort of 312 lb at 85 mph. In order to stay in keeping with current automotive practice, however, the low speed tractive effort requirement was increased to one-half the test weight or 2,150 lb. This level of tractive effort provides a capability for acceleration from 0 to 15 mph on a 30-percent grade in 6 sec.

The final specification for transmission performance in all four quadrants is shown in Fig. 2-4. Performance requirements for the second, third, and fourth quadrants were established in conjunction with the EPA and the transmission contractors. The second and third quadrant requirements are dictated largely by safety considerations.

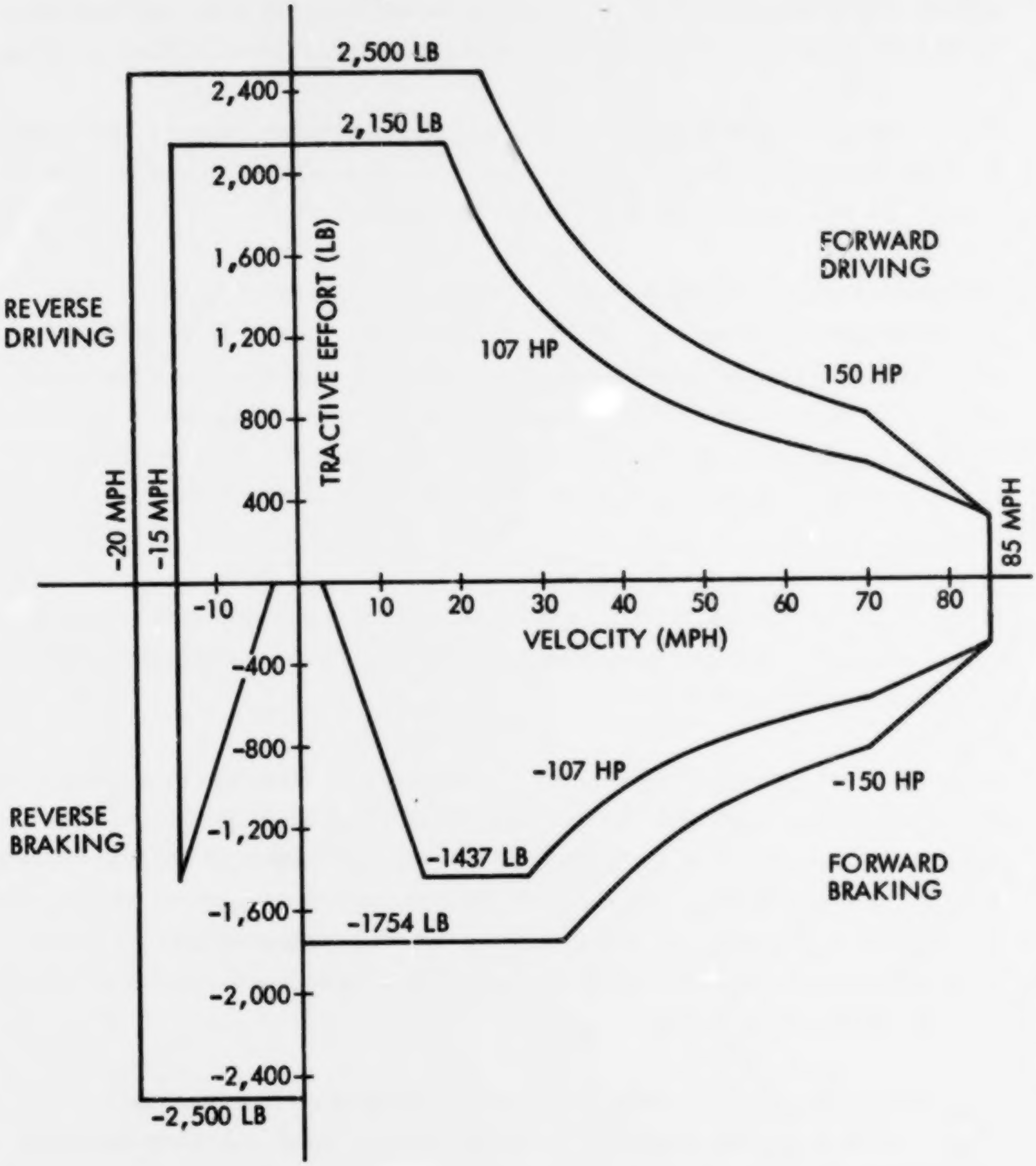


Fig. 2-4 Tractive Effort Vs. Velocity Requirements for Flywheel Drive System

The fourth quadrant requirements roughly mirror the first quadrant characteristics with lower requirements for tractive effort based on the reduced traction of the driven (rear) wheels under braking conditions. Discussions with the transmission contractors of the EPA/OAP Program indicated that these fourth-quadrant requirements would not penalize transmission design since this "mirror image" capability is inherent in the type of transmission under consideration.

In order to ensure that the transmission performance as specified is sufficient to cover all operating points in the dyno cycle, a plot was made of vehicle velocity versus tractive effort over the full dyno cycle. This plot is given in Fig. 2-5. If constant acceleration within each second of the cycle is assumed, each line of constant velocity represents an instantaneous change in tractive effort, and each line of constant tractive effort represents a change in velocity over a 1-sec interval. The actual plotting occurs in a generally counterclockwise direction because the velocity is roughly proportional to the time integral of tractive effort.

A comparison of Figs. 2-4 and 2-5 shows that all of the dyno cycle operation lies well within the specified tractive-effort/speed requirements.

Since the dyno cycle revision of November 10, 1970 employs artificial acceleration limits to facilitate dynamometer testing, a similar plot (Fig. 2-6) was also made for the more realistic original dyno cycle (July 15, 1970). Again, all the original dyno cycle operating points lie within the specified transmission requirements.

FLYWHEEL CHARACTERISTICS

As a starting point, the transmission contractors had available the information on flywheel characteristics contained in the final report of the Flywheel Feasibility Study and Demonstration (Ref. 1-1). Based on that previous study, certain other guidelines stipulated by EPA are as follows:

- Baseline maximum flywheel speed – 24,000 rpm
- Flywheel speed range – 1.5 to 1 minimum, 3 to 1 maximum

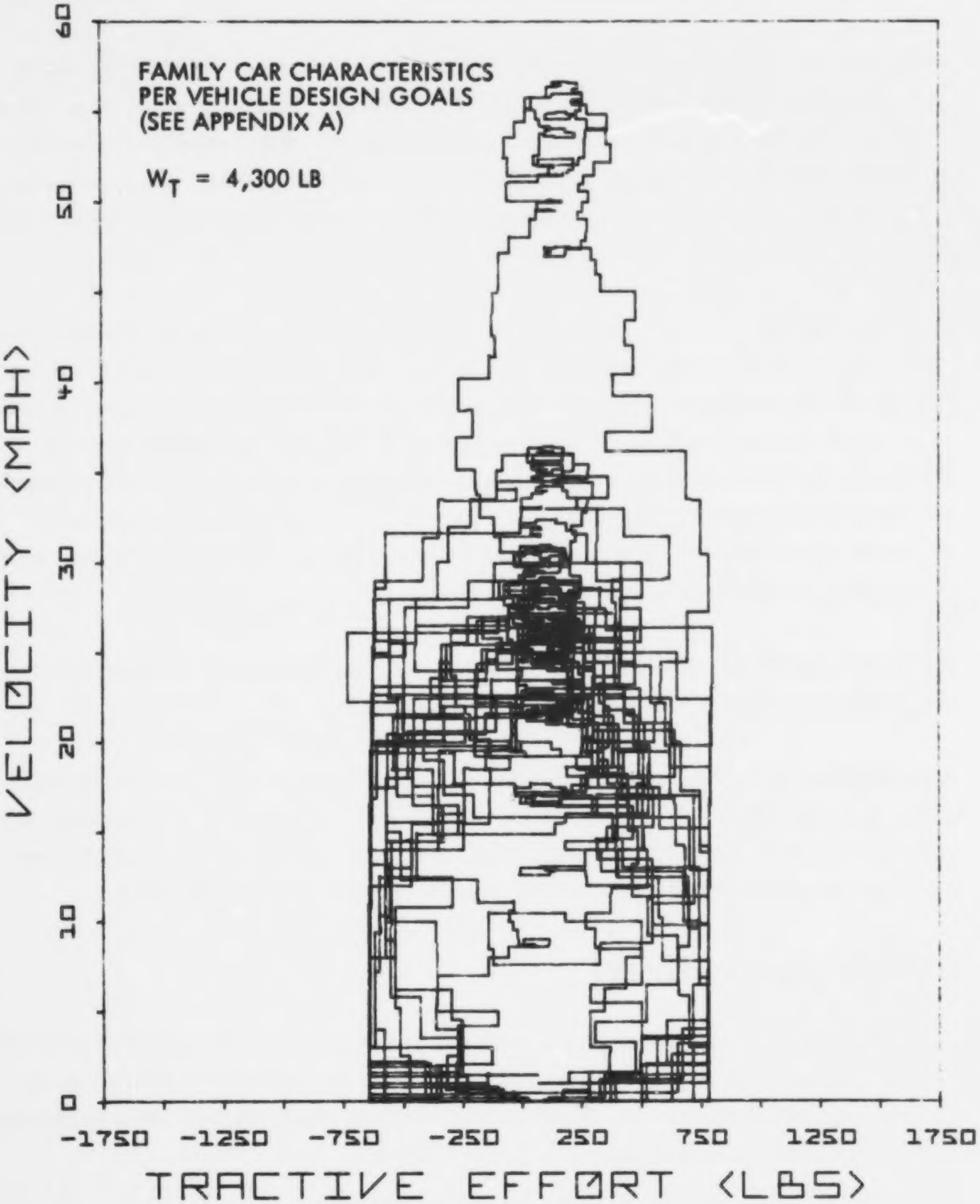


Fig. 2-5 Velocity Vs. Tractive Effort – Revised Dyno Cycle, November 10, 1970

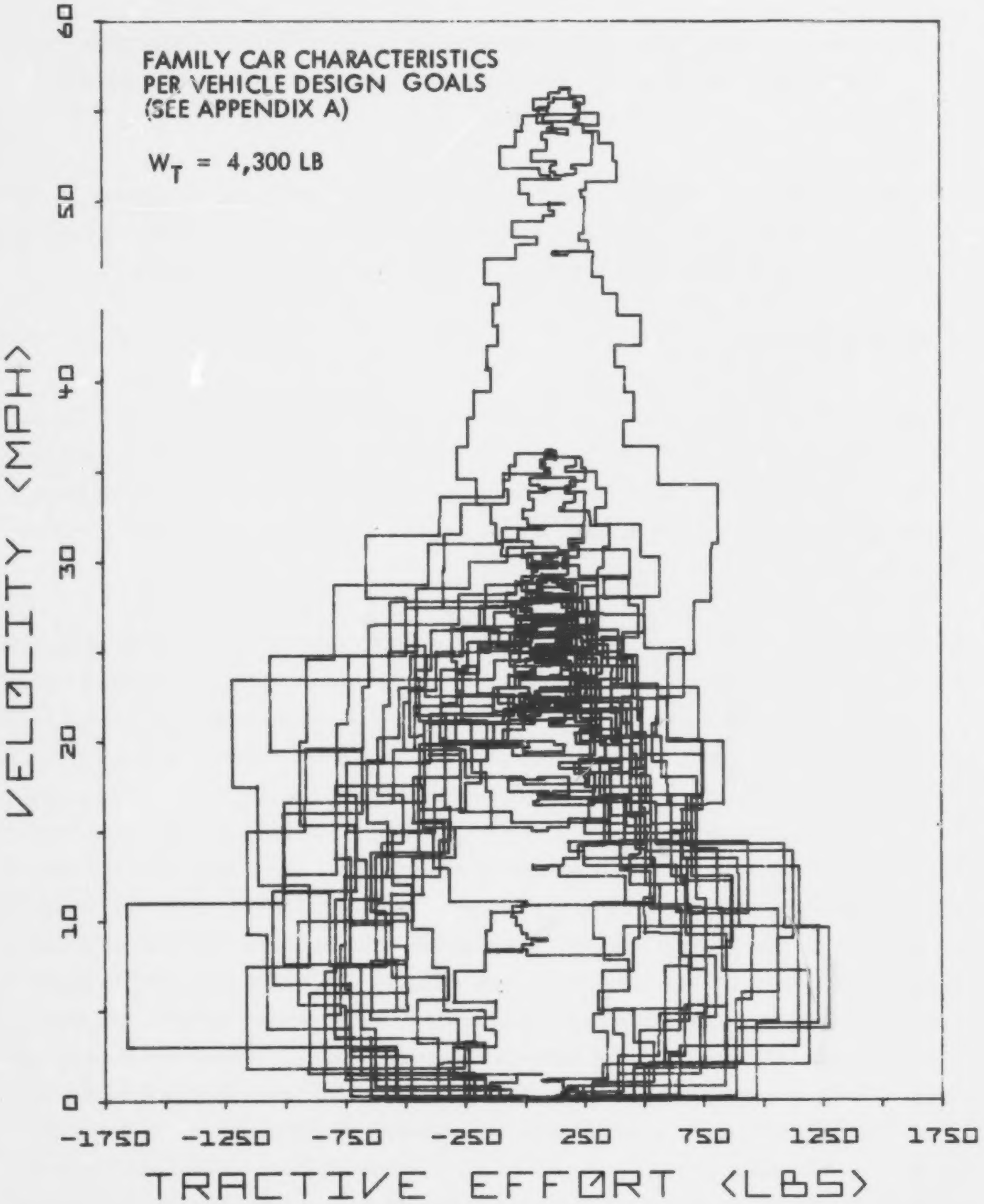


Fig. 2-6 Velocity Vs. Tractive Effort – Original Dyno Cycle, July 15. 1970

- Flywheel energy (usable) – Approximately equal to that of the specified vehicle (per Appendix A) at the maximum speed of 85 mph, i.e., approximately 0.5 hp-hr (0.373 kw-hr).

Detailed information concerning flywheel system losses and space requirements, in the form of layouts, was transmitted to the transmission contractors as they became available from the LMSC studies described in Sections 3 and 5 of this report.

SYSTEM CONTROL

The basic initial system control philosophy stipulated was that of maintaining a constant total kinetic energy (TKE) for the system. In other words, the heat engine output is controlled so as to hold, at a constant value, the sum of the kinetic energies of the flywheel and the vehicle. The TKE approach is described in greater detail in Ref. 1-1.

By direction of the EPA, a conventional front-engine, rear-wheel-drive configuration was to be used. Under heavy braking conditions, the rear wheels are lightly loaded, and the percentage of vehicle kinetic energy that can be recuperated into the flywheel is therefore rather small. The resultant loss in TKE could cause an immediately subsequent heavy acceleration to be degraded because of insufficient flywheel energy. This so-called "history dependence" is obviously objectionable and potentially dangerous. In order to assess the seriousness of this problem, an analysis of a full-stop, full-go maneuver was made, using the computer program /5.0 MANEUVER/ contained in Appendix C. Computer runs were made of the following maneuver: decelerate from the maximum vehicle speed of 85 mph with a braking force of 0.8 W_t to 0 mph and immediately re-accelerate to 85 mph. Efficiencies between flywheel and road, between engine and flywheel, and between engine and road were assumed to be 80 percent. The first computer run showed that the flywheel became exhausted during re-acceleration, resulting in a sudden loss in acceleration performance. In order to avoid the suddenness of this performance loss, an anticipatory control scheme was devised; the power normally available for acceleration was multiplied by the ratio of actual TKE to rated TKE. Thus, the low TKE condition which occurs upon re-acceleration causes the available flywheel power to be reduced such that the flywheel does not become depleted. Although this control scheme is probably not optimal, it is sufficient and represents a condition which can easily be approximated by the control system. The engine horsepower was 92.9, a value required to satisfy the Vehicle Design Goals (Appendix A) for maintaining 70 mph on a 5-percent grade for 100 sec. The 0-to-60-mph acceleration times are as follows:

Maneuver	Elapsed Time 0 to 60 mph (sec)
1st	12.34
2nd	19.21
3rd	19.21

The advantage of an intermittent engine rating (referred to the road) approaching the maximum road power is obvious; in the limiting case, where the engine power (referred to the road) is equal to or greater than the maximum required road horsepower, there are no history-dependence effects on performance.

Section 3

FLYWHEEL BURST DYNAMICS STUDY AND CONTAINMENT TESTING

Provision for personnel safety in the event of flywheel disintegration is of primary importance in the design of any system involving high energy flywheels. The probability of such disintegration can be made very small by proper flywheel design, material, and manufacturing techniques but it cannot be eliminated completely because of the possibility of external damage, material variability, and the indeterminate effect of the individual operating history upon the fatigue life of the flywheel. Accordingly, a significant portion of the total Flywheel Drive Systems Study program involved analysis of the dynamics of a bursting flywheel and the testing of a number of containment devices of different configurations.

ANALYSIS OF BURST DYNAMICS

KINETIC ENERGY DISTRIBUTION

The total kinetic energy of a flywheel after burst is distributed among the fragments as a combination of rotational and translational kinetic energy. Each fragment rotates about its center of gravity with an angular velocity ω equal to that of the flywheel at burst, while its center of gravity moves in a tangential direction with the velocity ωr, where r is the radial distance from the flywheel axis of rotation to the c.g. of the fragment.

Of particular interest, from the standpoint of burst containment, is the radial component of the translational energy because this portion of the total energy must be absorbed in deformation upon contact of the fragments with the containment ring. Analysis has shown this impact energy to be a function of the radial clearance between the containment ring and the flywheel at burst, as well as of the number, size, and shape of the burst fragments (See Appendix D). The fraction of total flywheel kinetic energy which appears as translational energy of the fragments increases with the number of fragments. The radial component of the translational energy is minimized by keeping the clearance between ring and flywheel at burst as small as possible.

RADIAL CLEARANCE REQUIREMENTS

Two principal factors are to be considered in determining the minimum practical radial clearance at speed between flywheel and ring. The first is the variation in the gap at operating speed due to the differential radial thermal expansion of flywheel and ring; this factor is minimized by evacuating the flywheel chamber to a low pressure so as to limit aerodynamic heating. In an operational system, the second factor affecting gap requirement is the tolerance build-up in the assembly, including deviation from concentricity between ring and flywheel. The design gap at rest is determined by adding the required gap at speed to the radial elongation resulting from maximum speed; the latter being readily determined from the flywheel geometry and material.

CONTAINMENT RING DESIGN CRITERIA

The containment ring was designed to supply the centripetal force necessary to maintain rotation of the flywheel fragments within the ring. Initial rough estimates of ring dimensions were determined by setting a value for the cross-sectional area of the ring multiplied by the tensile stress of the ring material equal to the total tangential force over a half-section of the flywheel at burst.

The validity of this approach is reduced as the radial thickness of the ring increases. An attempt was made to account for the non-uniformity in tangential stress over the ring in the radial direction by treating the ring as a pressure vessel. This condition is approximated by a flywheel burst which results in a large number of small pieces, with a small radial gap. For a ring of given dimensions, this approach results in a higher tangential stress in the inner portion of the ring than that resulting from the assumption of uniform stress. Conversely, if the inner fiber design stress is held to the same value as that computed on the basis of force divided by area F/A, the ring dimensions increase. Typical calculations of containment ring dimensions are shown in Appendix E.

Further improvement in analytical determination of containment ring performance was afforded by a theoretical ring analysis method developed under a Lockheed-funded Independent Development Program. This analysis was initially based on the assumption of a Bernoulli-Euler ring subjected to circumferentially moving forces, representative of those imposed by the flywheel fragments after burst. Subsequently, the method was refined to account for bending stresses and to permit application to rings with non-isotropic characteristics, such as the glass-filament/resin composites. Through programming for computer operation with a Tymshare terminal and peripheral plotter, quick generation was possible of curves showing the time variation (over any desired portion of the ring) of radial and circumferential strain, shear strain, longitudinal strain, and radial and circumferential displacements.

FLYWHEEL CONTAINMENT TESTS

Although the analytical work described previously provided a basis for the initial design of the containment rings, verification of the design was accomplished by spin tests at energy levels representative of those required for the family car.

TEST TECHNIQUE

Spin tests were conducted in an evacuated spin pit. The flywheel was suspended from a vertical spindle and driven to speed by an air turbine. The containment ring was suspended from the upper plate of the pit by three equally spaced hangers, and was positioned with adjusting screws to be concentric with the flywheel.

The initial gap between ring and flywheel is listed in Table F-1 of Appendix F. Determination of the gap required for each test accounted not only for the factors discussed earlier under Analysis of Burst Dynamics but also for the gyrodynamic behavior of the flywheel in this particular test configuration. At speeds below the critical speed of the system, the flywheel tends to rotate about the centerline of the drive shaft. This axis can be accurately located in relation to the inside diameter of the containment ring. However, as rotational speed exceeds the critical speed, the center of rotation of the flywheel shifts to its center of mass. Precise balancing techniques make the flywheel eccentricity, per se, very small, i.e., on the order of $20\,\mu$in., but it was not feasible to balance the entire flywheel-hub-spindle assembly as a unit.

To determine the actual assembly radial eccentricity resulting from this effect, a series of spin tests was conducted. The flywheel was driven through the critical speed range while measurements of radial displacement were taken at three points equally spaced about the periphery. The average radial displacement for several runs was 0.037 in. This displacement represents the radial clearance which must be added to the radial elongation of the flywheel in order to prevent the flywheel from touching the ring during spin up.

TEST MATERIALS

It was desirable to use a test flywheel capable of operating at an energy level of approximately 1 hp-hr, or approximately 50 percent greater than requirements of the family car. This test flywheel design was approximately the same energy as the family car flywheel at burst, but was of a geometry more suitable for burst testing.

Flywheel design tradeoff analysis and burst tests previously conducted under a Lockheed-funded Independent Development Program had shown that the problems of burst containment were aggravated by using relatively thin flywheels, e.g., pierced disc flywheels 15 in. in diameter and 0.7 in. thick. In containment rings fabricated from a composite of glass filaments and resin, the forces from the burst flywheel tended to cause shear failure of the resin matrix. As a result, there was a tendency for annular segments of the ring to be thrown off intact from upper and lower surfaces. In axially thin rings, this essentially ineffective material accounted for an appreciable fraction of the total material in the ring. In axially thicker (and radially thinner) rings, the loss of strength from this effect was less significant.

Another factor in sizing the flywheel was the constraint on the overall diameter of the flywheel/containment ring, as imposed by the requirement for fitting the flywheel into a family-type car. Accordingly, an outside diameter of 13 in. was chosen for the flywheel. For convenience, an inside diameter of 3 in. and a nominal burst speed of 24,000 rpm were chosen. A thickness of 3.5 in. provided the desired kinetic energy of approximately 1 hp-hr.

Kinetic energy of the flywheel at burst was controlled by cutting radial notches in the inside diameter. The tangential stress at burst is related to notch depth ℓ by the following equation:

$$\sigma_{abs} = \frac{\rho\omega^2}{3g}\left(\frac{R_o^3 - R_i^3}{R_o - R_i - \ell}\right) \qquad \text{(Ref. 3-1)}$$

The notches were located so as to cause the flywheel to burst into three sectorial fragments, one of 90 deg and two of 135 deg. It was considered that this configuration would approximate the most severe condition from the standpoint of containment. Initial calculations of required notch length were based on the assumption that absolute bursting stress σ_{abs} was equal to the tensile yield stress of the material multiplied by a factor of 1.06 to account for the biaxial stress field existing in the flywheel. Following each test, σ_{abs} was revised to reflect the results of the test in order to improve the accuracy of subsequent calculations.

Two basic containment ring configurations were tested – rings made of a homogeneous, isotropic material (e.g., steel), and rings fabricated from a composite of glass fiber and resin matrix wound on a steel liner. Design details of the various test rings are presented in Appendix F.

TEST RESULTS

The tests demonstrated the following mechanisms through which the kinetic energy of the flywheel was dissipated without external damage:

- Transfer of momentum to the surrounding ring before flywheel disintegration
- Containment of the burst fragments after flywheel disintegration

Two cases of momentum transfer occurred in which the flywheel elongated radially under load to fill the gap between the flywheel and the ring. When contact occurred, the ring acquired angular velocity while the flywheel decelerated rapidly. The ring and flywheel then spun to a stop with only minor scuffing from contact with the sides and bottom of the pit. The highest flywheel speed at which this occurred was 23,840 rpm, corresponding to an energy level of 0.94 hp-hr, with a radial gap (initial) of 0.075 in. Examination of the flywheel following this test revealed pronounced strain lines emanating from the apex of each of the three 0.08-in. deep V-grooves cut into the bore, indicating plastic deformation of the flywheel. This result is shown in Fig. 3-1.

Two tests resulted in flywheel bursts with complete containment of the fragments within the ring. In the first test, a 20.3-in. diameter, 192-lb containment ring of SAE-4340 steel with an ultimate tensile strength F_{t_u} of 150,000 psi was used. Burst occurred at an energy level of 0.86 hp-hr (22,820 rpm). The result is shown in Fig. 3-2. The weight of the steel ring was 1.5 times the flywheel weight. The second test was performed with a containment ring consisting of an 0.5-in.-thick liner of SAE-4340 steel (F_{t_u} = 125,000 psi) wound to a radial thickness of 7 in. with "E" glass tape in a polyester resin matrix. Burst occurred at 16,750 rpm with an energy level of 0.46 hp-hr (significantly below the 1 hp-hr level). The results of this test are shown in Fig. 3-3. Rotation was in the clockwise direction. Figure 3-3a shows the untouched results of the test. For clarity, the small pieces of debris were removed with a vacuum cleaner; the result of this action is presented in Fig. 3-3b. The flywheel pieces were then removed to show the failure of the steel liner; this is illustrated in Fig. 3-3c. The glass ring, including liner, weighed 167 lb; again, the weight of the flywheel was 125 lb.

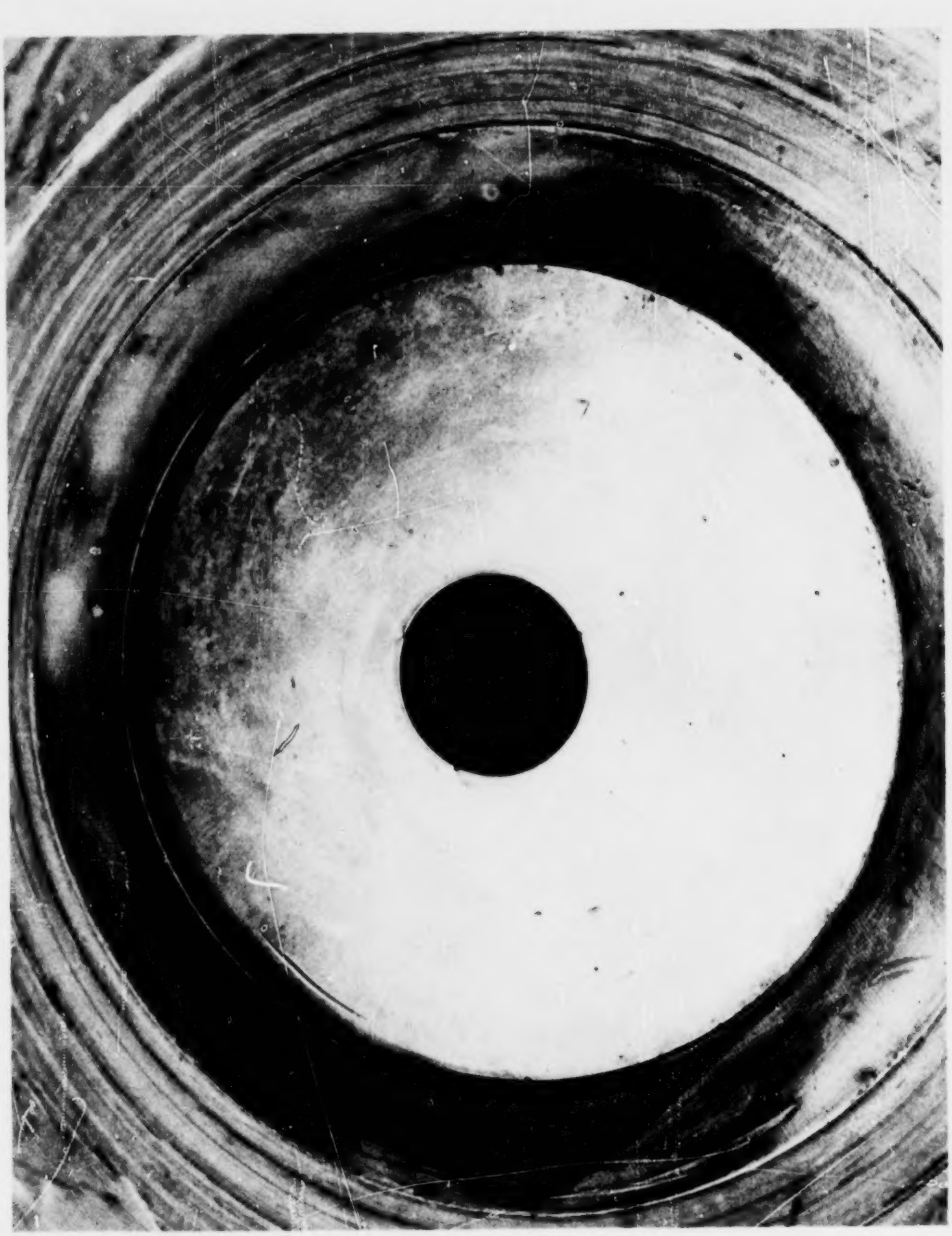


Fig. 3-1 Momentum Transfer Between Flywheel and Ring, Showing Strain Lines at Apex of Notches in Bore

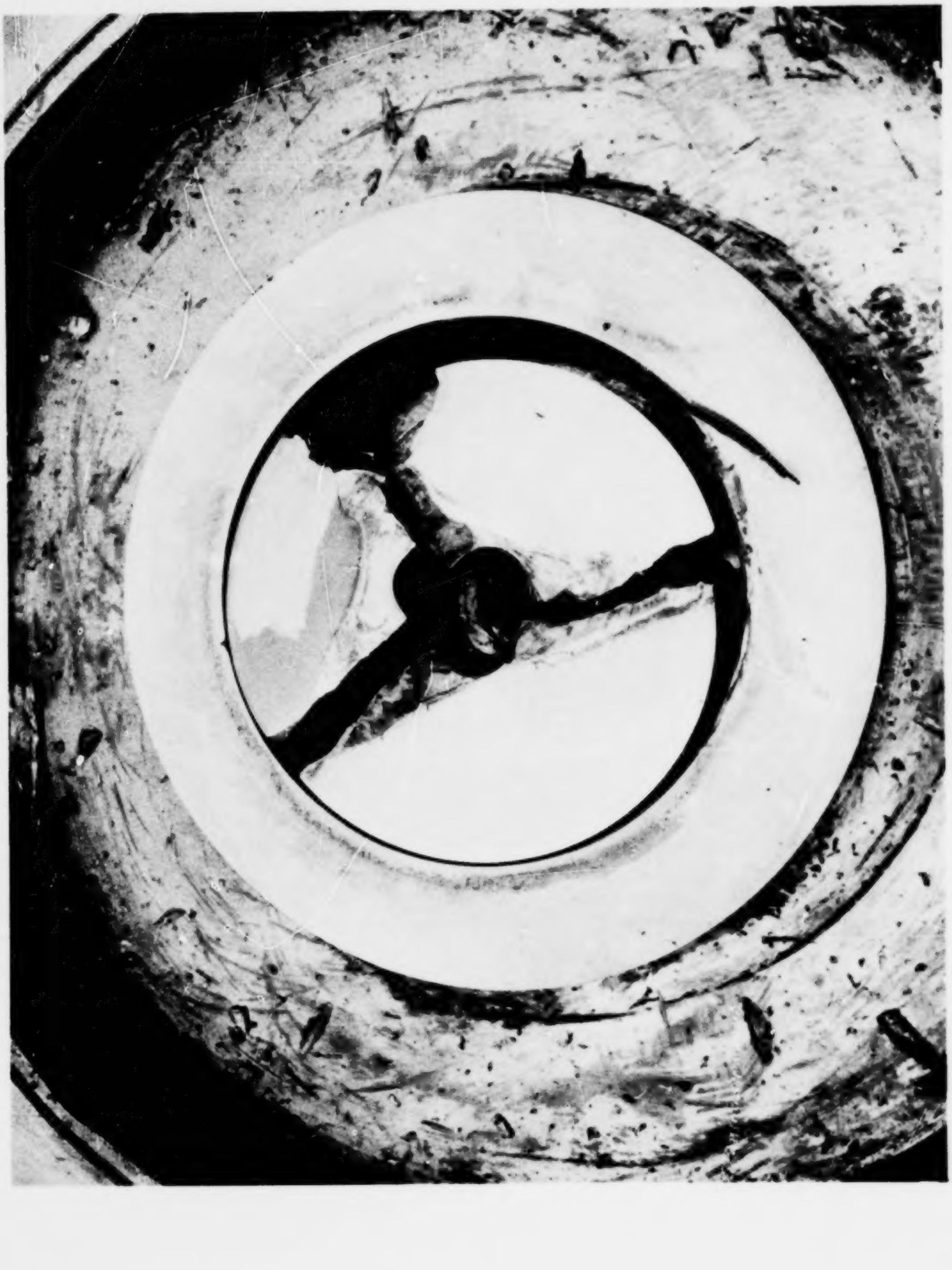


Fig. 3-2 Burst Containment by Steel Ring

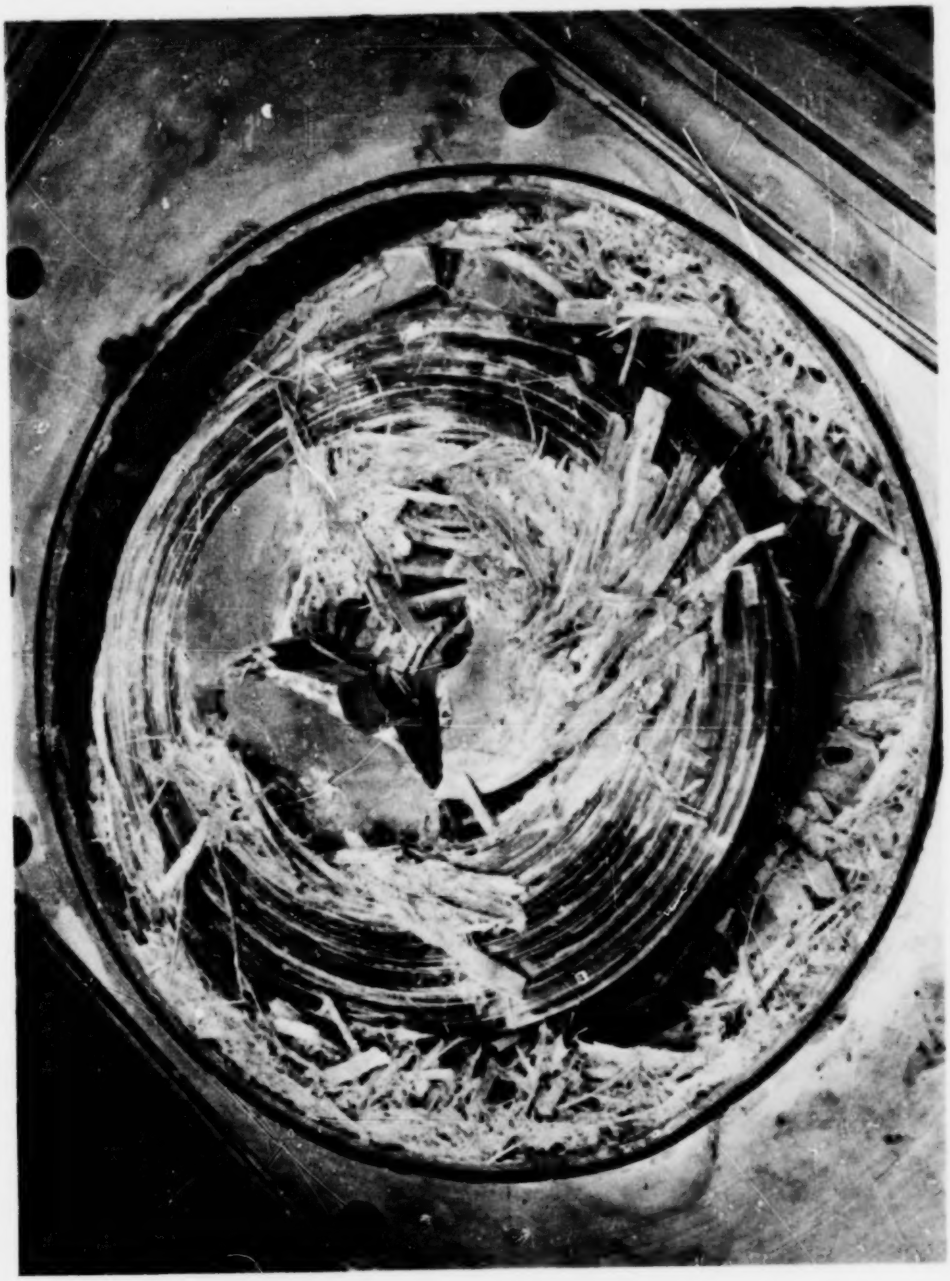


Fig. 3-3a View Upon Opening Test Pit

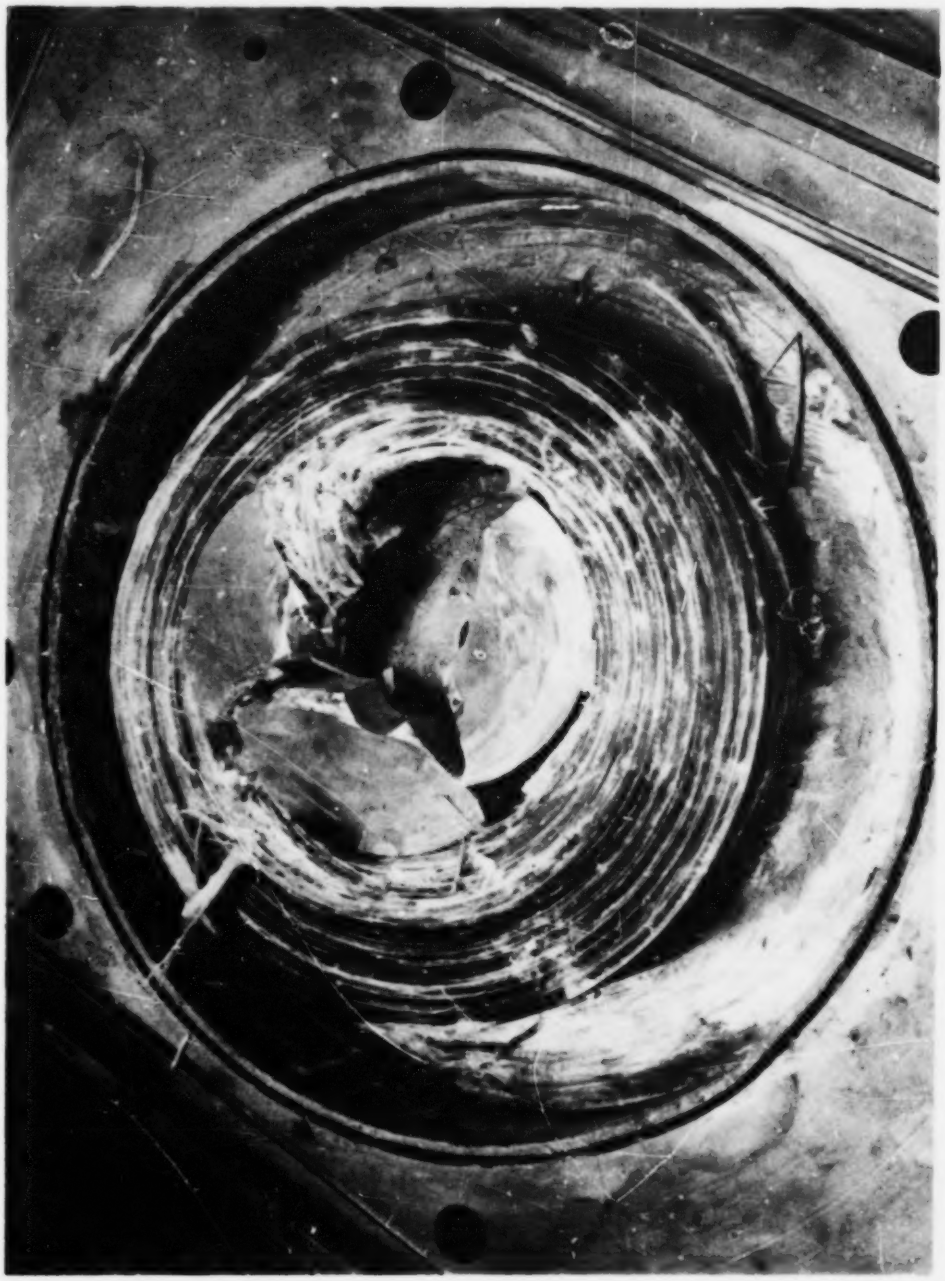


Fig. 3-3b View After Removal of Small Fragments

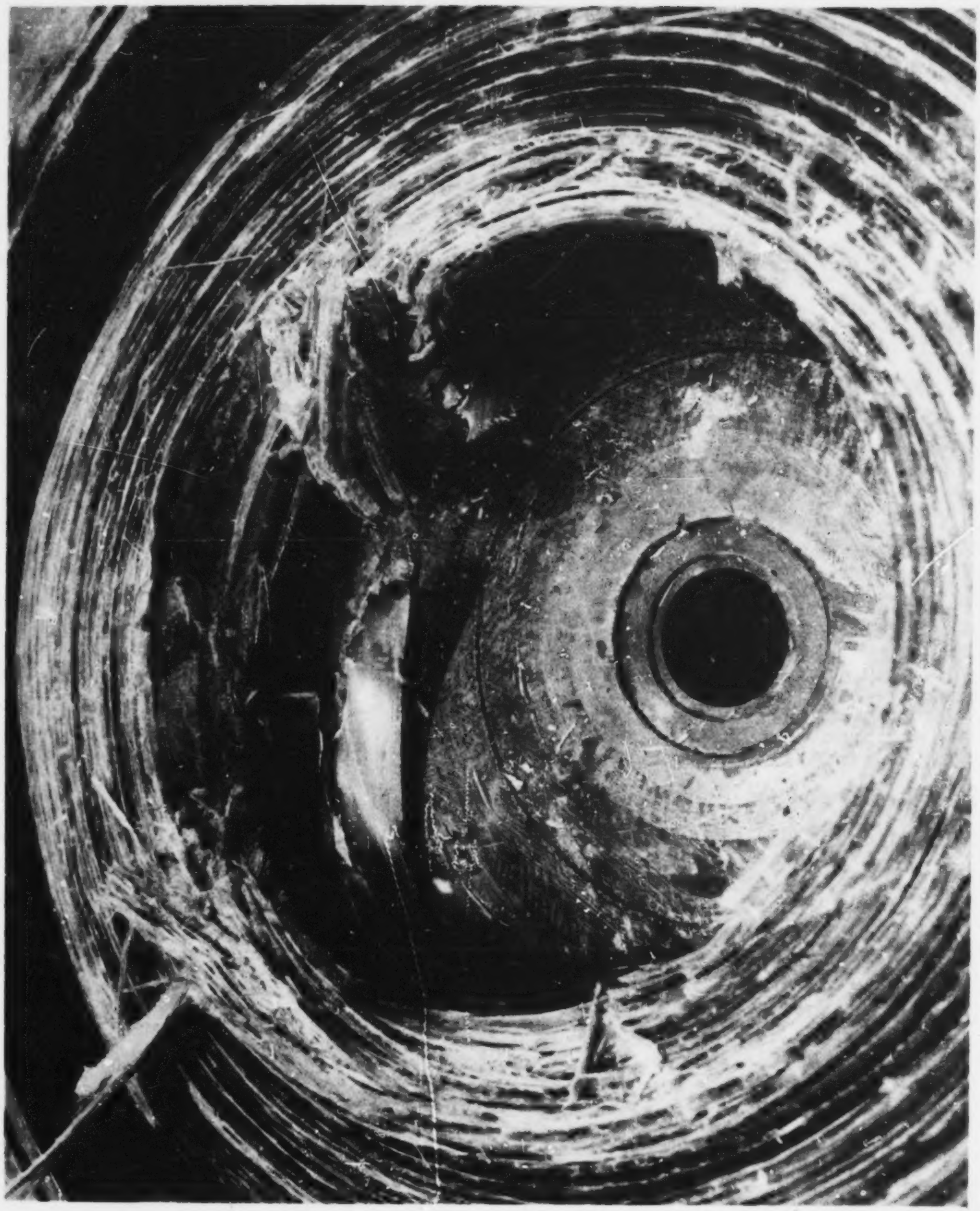


Fig. 3-3c View After Removal of Flywheel Fragments

Three tests resulted in flywheel bursts in which the containment ring failed. The rings were fabricated of "E" glass/epoxy on a steel liner. The first of these rings tested (Type B, Appendix E) was wound with glass filament in an epoxy matrix. There was evidence that annular sections had been thrown out in a virtually intact condition from the upper and lower surfaces of the ring with consequent reduction in the effective strength of the ring. This failure was caused by shear failure of the matrix. To improve the axial tensile properties, subsequently fabricated rings used woven glass fabric or tape. Although the woven construction resulted in some reduction in filament strength because of the overlap, the axially oriented filaments provided considerably higher strength in the axial direction of the ring, and eliminated the loss of material as previously noted.

A complete chronology of the testing program is presented in Appendix F.

CONCLUSIONS

A series of tests included two cases of successful momentum transfer (where the flywheel did not burst, but grew until it engaged the containment ring) and two cases of successful burst containment. In both tests where burst containment was affected, however, the containment energy density (i.e., the ratio of flywheel energy at burst to the weight of the containment ring) was unsatisfactory. Until such time that lightweight containment rings become available, the conventional automotive practice of low stress flywheels appears to be the more effective approach to safety.

Section 4
SAFETY ANALYSIS

FAULT TREE ANALYSIS

The purpose of fault tree analysis is to identify, evaluate, and eliminate or control potential hazards as early in the life cycle as possible. Fault tree analysis involves detailed examination of the particular design to evaluate failure effects, man-machine relationships, and all aspects of system development and operation. The distinction between fault tree and gross hazard safety analysis is shown in Fig. 4-1. A fault tree is a graphical representation of the relationship between certain specific events and an ultimate undesired event. In measuring the level of safety of an operational product, the initial step is a definition of the particular undesirable event or events involved. Each fault tree, because it is single-event oriented, must be constructed to include only one most undesired event. There are several other events leading to this "top" event which are analyzed in relationship to such occurrence. This situation makes it mandatory to establish terminology for the top event that will encompass the lesser events, individually or collectively. One objective is to determine how the system, including the personnel involved with system operation and maintenance, could fail so as to cause the undesired series of happenings.

A fault tree is constructed by properly relating all possible sequences of events that, upon occurrence, lead to the undesired result. Beginning at the top, the fault tree graphically depicts the paths that lead to each event from various lower level events. This does not imply that higher level events have a higher probability of occurrence than lower level events. In fact, the opposite may be the case.

The causal relationships between events are described by logic gates. Three basic logic gates are used: AND, OR, and INHIBIT. The AND and OR gates represent the

GROSS HAZARD	FAULT TREE
DEFINITIVE	DIAGRAMMATIC
DESCRIPTIVE TERMINOLOGY	GRAPHIC LOGIC SYMBOLS
CRITICAL AREAS	CRITICAL PATHS
USUALLY CAUSE TO EFFECT	ALWAYS EFFECT TO CAUSE
CONCEPTS	SPECIFIC EVENTS
INHERENT HAZARDS	UNDESIRED EVENT
SYSTEM SAFETY	SYSTEM ORIENTED ULTIMATE UNDESIRED EVENT
COMPREHENSIVE	SINGLE EVENT ORIENTED
HUMAN ERRORS	HUMAN ERRORS AS EVENTS
QUALITATIVE ONLY	CAN BE QUANTITATIVE
POSSIBILITY	CAN USE NUMERICAL PROBABILITY
INITIAL INVESTIGATION	ITERATIVE PROCESS
ESTABLISHING DESIGN CRITERIA	EXAMINING DESIGNS

Fig. 4-1 Safety Analyses

fundamental Boolean functions that form the basis for all logic analysis. If an event is sufficient but not necessary to cause the next higher event to occur, an OR gate is used. If an event is necessary but not sufficient to cause the next higher event to take place, an AND gate is used. The INHIBIT gate is a variation of the AND gate and applies conditional probabilities to a fault sequence. The logic symbols used in fault tree analysis are shown in Fig. 4-2.

The fault tree can be directed to answer various questions by properly defining the ultimate undesired event for each case. The ultimate undesired event has been defined in the following ways for this safety analysis:

- Loss of human life or health caused by the automobile
- Event causing death or injury, vehicle loss, or major system damage or requiring immediate action for survival
- Fatality resulting from a traffic accident
- Fatality due to flywheel failure caused by impact

Cause and effect can be established between traffic accidents and death and injury. It is much more difficult, however, to establish a correlation between air pollution and deterioration of human health on a nationwide basis. As a result, an increase in traffic injuries and fatalities cannot be justified as a price to pay for a decrease in the detrimental effects of air pollution.

DEVELOPING THE FAULT TREE

The fault tree for the total vehicle (Fig. 4-3) provides a comprehensive assessment of the safety hazards inherent in flywheel hybrid vehicles. The top undesired event for this diagram is "causing death or injury, vehicle loss, or major system damage, or requiring immediate action for survival."

In developing the fault tree shown in Fig. 4-3, the following areas involving possible contribution to occurrence of the top undesired event were considered:

- Operational, collision, and maintenance safety
- Fail-safe design

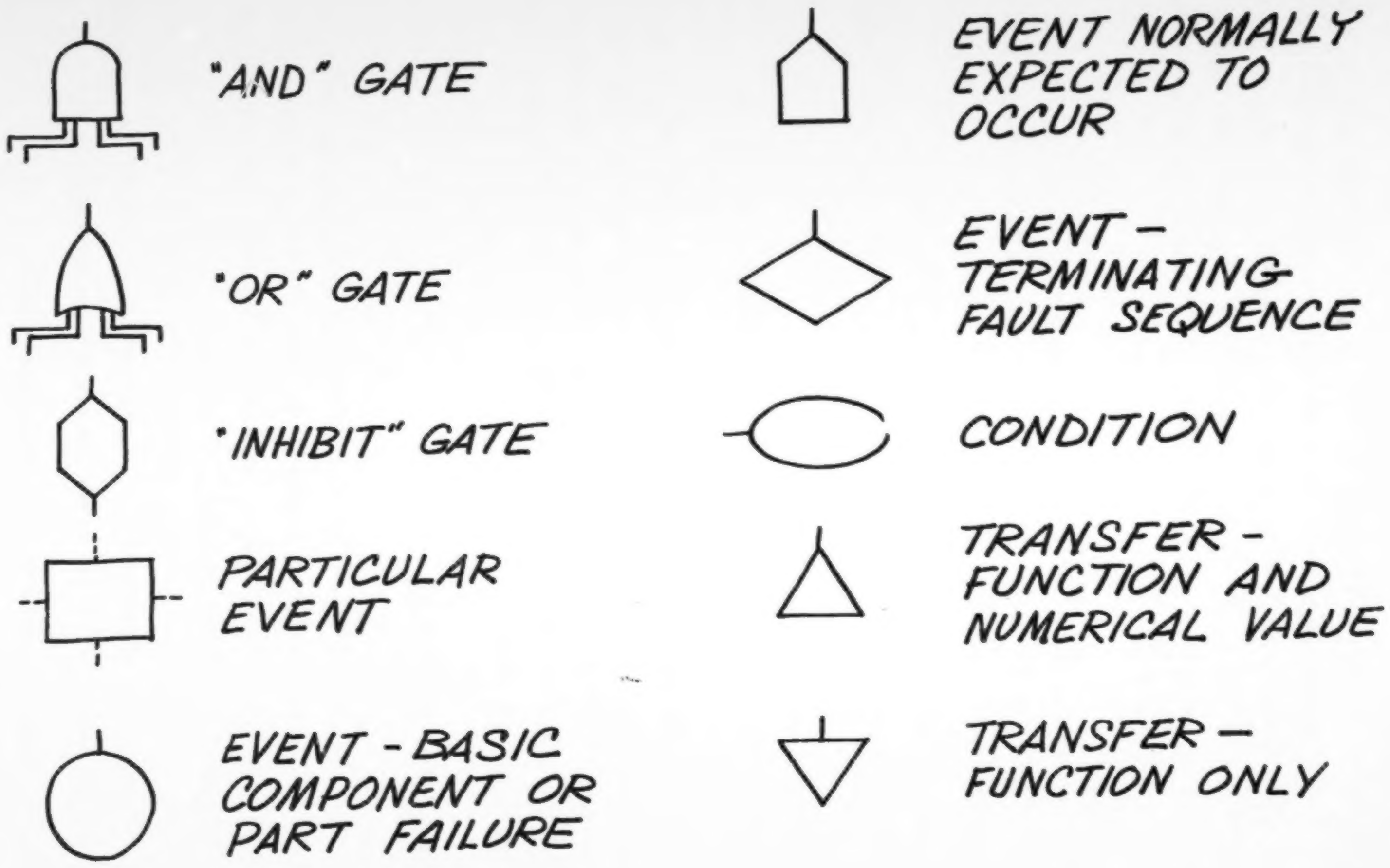

"AND" GATE
"OR" GATE
"INHIBIT" GATE
PARTICULAR EVENT
EVENT - BASIC COMPONENT OR PART FAILURE
EVENT NORMALLY EXPECTED TO OCCUR
EVENT - TERMINATING FAULT SEQUENCE
CONDITION
TRANSFER - FUNCTION AND NUMERICAL VALUE
TRANSFER - FUNCTION ONLY

Fig. 4-2 Fault Tree Symbols

- Human error analysis
- Prevention of inadvertent actuation of critical controls
- Resistance to shock damage
- Compatibility of materials
- Fire ignition propagation sources, and protection

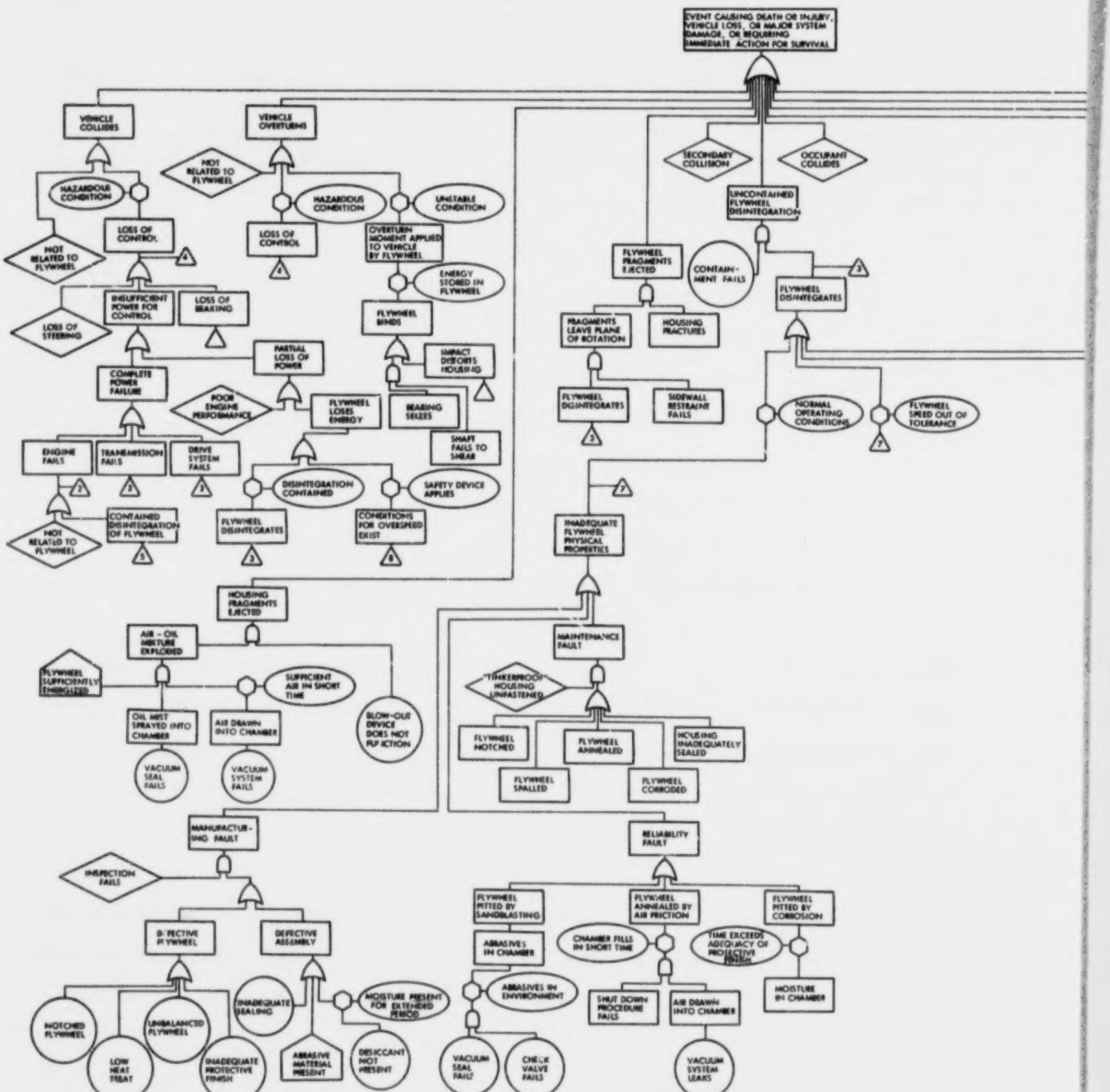
Furthermore, potential hazards were identified which could lead to the undesired event. They include the following:

- Flywheel disintegration
- Dislodged flywheel, flywheel assembly, or engine flywheel installation
- Flywheel kinetic energy transferred into heat
- Torque transferred from flywheel into vehicle
- No energy stored in flywheel when required
- Misleading control feedback to driver
- Loss of power boost to brakes and steering
- No braking or insufficient braking when required
- Insufficient, uneven, interrupted, or excessive torque to wheels

Moving down to the lower levels of this tree, losses of component functions which affect the hybrid system drive operation can be identified. Included are signals from the speedometer and engine and flywheel tachometers; commands from the PRNDL setting, accelerator, and brake; electric power; hydraulic fluid; and brake fluid, lining, and adjustment.

Safe operation of the hybrid system can also be affected by rotation malfunction of various power shafts, attached to the engine or flywheel, within the transmission or delivering power to the road. These malfunctions can include any of the following:

- Lack of rotation
- Abrupt stop
- Gradual stop
- RPM too slow


EVENT CAUSING DEATH OR INJURY, VEHICLE LOSS, OR MAJOR SYSTEM DAMAGE, OR REQUIRING IMMEDIATE ACTION FOR SURVIVAL
VEHICLE COLLIDES
HAZARDOUS CONDITION
NOT RELATED TO FLYWHEEL
LOSS OF CONTROL
4
INSUFFICIENT POWER FOR CONTROL
LOSS OF BRAKING
LOSS OF STEERING
COMPLETE POWER FAILURE
PARTIAL LOSS OF POWER
POOR ENGINE PERFORMANCE
FLYWHEEL LOSES ENERGY
ENGINE FAILS
TRANSMISSION FAILS
DRIVE SYSTEM FAILS
2
2
2
NOT RELATED TO FLYWHEEL
CONTAINED DISINTEGRATION OF FLYWHEEL
5
DISINTEGRATION CONTAINED
SAFETY DEVICE APPLIES
FLYWHEEL DISINTEGRATES
3
CONDITIONS FOR OVERSPEED EXIST
8
VEHICLE OVERTURNS
NOT RELATED TO FLYWHEEL
HAZARDOUS CONDITION
UNSTABLE CONDITION
LOSS OF CONTROL
4
OVERTURN MOMENT APPLIED TO VEHICLE BY FLYWHEEL
ENERGY STORED IN FLYWHEEL
FLYWHEEL BINDS
IMPACT DISTORTS HOUSING
BEARING SEIZES
SHAFT FAILS TO SHEAR
SECONDARY COLLISION
OCCURANT COLLIDES
UNCONTAINED FLYWHEEL DISINTEGRATION
CONTAIN-MENT FAILS
3
FLYWHEEL DISINTEGRATES
NORMAL OPERATING CONDITIONS
FLYWHEEL SPEED OUT OF TOLERANCE
7
FLYWHEEL FRAGMENTS EJECTED
FRAGMENTS LEAVE PLANE OF ROTATION
HOUSING FRACTURES
FLYWHEEL DISINTEGRATES
3
SIDEWALL RESTRAINT FAILS
7
INADEQUATE FLYWHEEL PHYSICAL PROPERTIES
HOUSING FRAGMENTS EJECTED
AIR - OIL MIXTURE EXPLODED
FLYWHEEL SUFFICIENTLY ENERGIZED
SUFFICIENT AIR IN SHORT TIME
OIL MIST SPRAYED INTO CHAMBER
AIR DRAWN INTO CHAMBER
BLOW-OUT DEVICE DOES NOT FUNCTION
VACUUM SEAL FAILS
VACUUM SYSTEM FAILS
MAINTENANCE FAULT
"TINKERPROOF" HOUSING UNFASTENED
FLYWHEEL NOTCHED
FLYWHEEL ANNEALED
HOUSING INADEQUATELY SEALED
FLYWHEEL SPALLED
FLYWHEEL CORRODED
MANUFACTURING FAULT
INSPECTION FAILS
DEFECTIVE FLYWHEEL
DEFECTIVE ASSEMBLY
NOTCHED FLYWHEEL
LOW HEAT TREAT
UNBALANCED FLYWHEEL
INADEQUATE PROTECTIVE FINISH
INADEQUATE SEALING
MOISTURE PRESENT FOR EXTENDED PERIOD
ABRASIVE MATERIAL PRESENT
DESICCANT NOT PRESENT
RELIABILITY FAULT
FLYWHEEL PITTED BY SANDBLASTING
ABRASIVES IN CHAMBER
ABRASIVES IN ENVIRONMENT
VACUUM SEAL FAILS
CHECK VALVE FAILS
FLYWHEEL ANNEALED BY AIR FRICTION
CHAMBER FILLS IN SHORT TIME
SHUT DOWN PROCEDURE FAILS
AIR DRAWN INTO CHAMBER
VACUUM SYSTEM LEAKS
FLYWHEEL PITTED BY CORROSION
TIME EXCEEDS ADEQUACY OF PROTECTIVE FINISH
MOISTURE IN CHAMBER

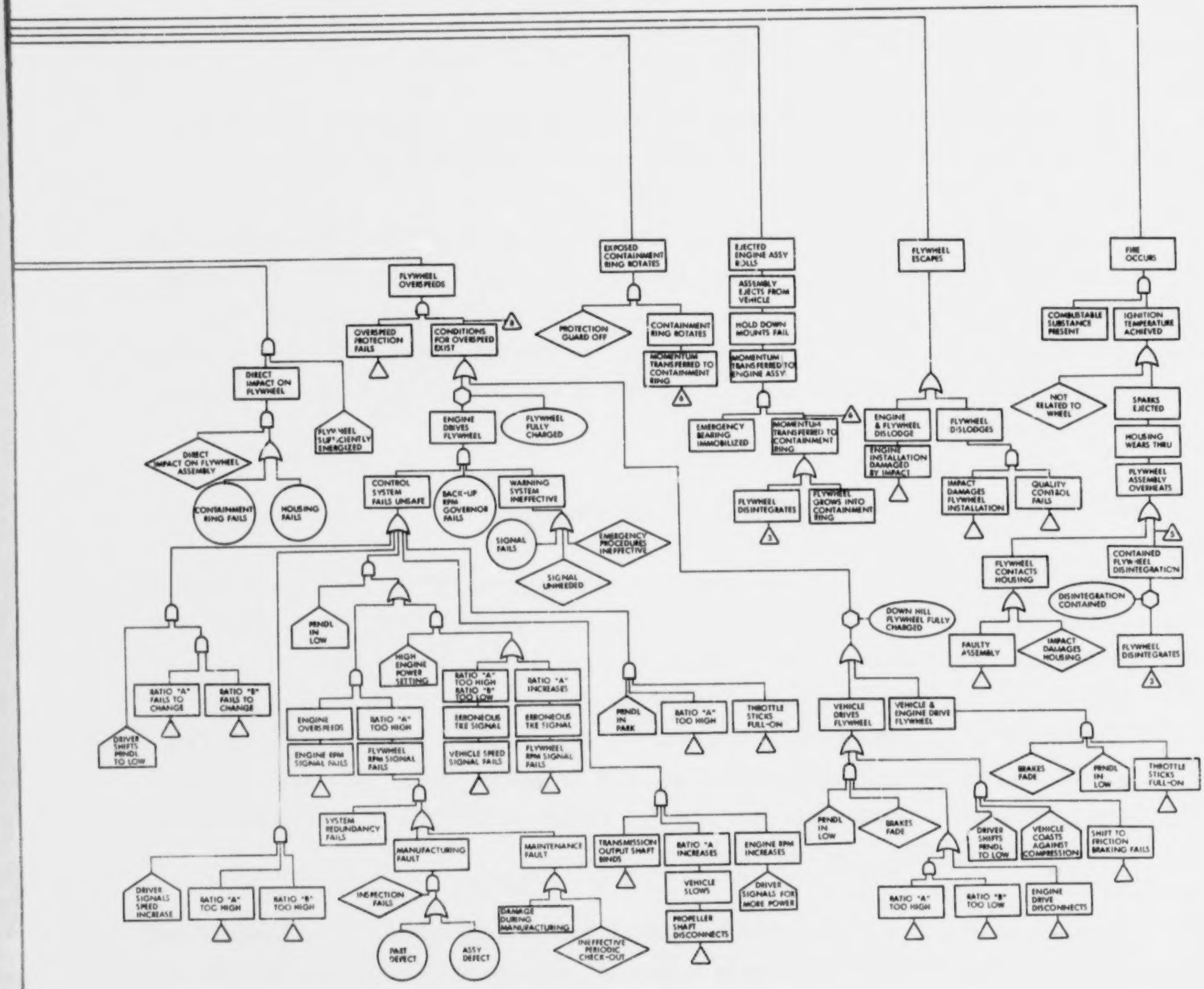

EXPOSED CONTAINMENT RING ROTATES
EJECTED ENGINE ASSY ROLLS
FLYWHEEL ESCAPES
FIRE OCCURS
FLYWHEEL OVERSPEEDS
OVERSPEED PROTECTION FAILS
CONDITIONS FOR OVERSPEED EXIST
8
PROTECTION GUARD OFF
CONTAINMENT RING ROTATES
MOMENTUM TRANSFERRED TO CONTAINMENT RING
6
ASSEMBLY EJECTS FROM VEHICLE
HOLD DOWN MOUNTS FAIL
MOMENTUM TRANSFERRED TO ENGINE ASSY
COMBUSTABLE SUBSTANCE PRESENT
IGNITION TEMPERATURE ACHIEVED
DIRECT IMPACT ON FLYWHEEL
FLYWHEEL SUFFICIENTLY ENERGIZED
DIRECT IMPACT ON FLYWHEEL ASSEMBLY
CONTAINMENT RING FAILS
HOUSING FAILS
ENGINE DRIVES FLYWHEEL
FLYWHEEL FULLY CHARGED
EMERGENCY BEARING IMMOBILIZED
MOMENTUM TRANSFERRED TO CONTAINMENT RING
6
ENGINE & FLYWHEEL DISLODGE
ENGINE INSTALLATION DAMAGED BY IMPACT
FLYWHEEL DISLODGES
NOT RELATED TO WHEEL
SPARKS EJECTED
HOUSING WEARS THRU
FLYWHEEL ASSEMBLY OVERHEATS
CONTROL SYSTEM FAILS UNSAFE
BACK-UP RPM GOVERNOR FAILS
WARNING SYSTEM INEFFECTIVE
SIGNAL FAILS
EMERGENCY PROCEDURES INEFFECTIVE
SIGNAL UNHEEDED
FLYWHEEL DISINTEGRATES
3
FLYWHEEL GROWS INTO CONTAINMENT RING
IMPACT DAMAGES FLYWHEEL INSTALLATION
QUALITY CONTROL FAILS
5
FLYWHEEL CONTACTS HOUSING
CONTAINED FLYWHEEL DISINTEGRATION
DISINTEGRATION CONTAINED
DOWN HILL FLYWHEEL FULLY CHARGED
FAULTY ASSEMBLY
IMPACT DAMAGES HOUSING
FLYWHEEL DISINTEGRATES
3
PRNDL IN LOW
HIGH ENGINE POWER SETTING
RATIO "A" TOO HIGH RATIO "B" TOO LOW
RATIO "A" INCREASES
RATIO "A" FAILS TO CHANGE
RATIO "B" FAILS TO CHANGE
DRIVER SHIFTS PRNDL TO LOW
ENGINE OVERSPEEDS
RATIO "A" TOO HIGH
ENGINE RPM SIGNAL FAILS
FLYWHEEL RPM SIGNAL FAILS
ERRONEOUS TRE SIGNAL
VEHICLE SPEED SIGNAL FAILS
ERRONEOUS TRE SIGNAL
FLYWHEEL RPM SIGNAL FAILS
PRNDL IN PARK
RATIO "A" TOO HIGH
THROTTLE STICKS FULL-ON
VEHICLE DRIVES FLYWHEEL
VEHICLE & ENGINE DRIVE FLYWHEEL
BRAKES FADE
PRNDL IN LOW
THROTTLE STICKS FULL-ON
SYSTEM REDUNDANCY FAILS
MANUFACTURING FAULT
MAINTENANCE FAULT
TRANSMISSION OUTPUT SHAFT BINDS
RATIO "A INCREASES
ENGINE RPM INCREASES
VEHICLE SLOWS
DRIVER SIGNALS FOR MORE POWER
PROPELLER SHAFT DISCONNECTS
PRNDL IN LOW
BRAKES FADE
DRIVER SHIFTS PRNDL TO LOW
VEHICLE COASTS AGAINST COMPRESSION
SHIFT TO FRICTION BRAKING FAILS
DRIVER SIGNALS SPEED INCREASE
RATIO "A" TOO HIGH
RATIO "B" TOO HIGH
INSPECTION FAILS
PART DEFECT
ASSY DEFECT
DAMAGE DURING MANUFACTURING
INEFFECTIVE PERIODIC CHECK-OUT
RATIO "A" TOO HIGH
RATIO "B" TOO LOW
ENGINE DRIVE DISCONNECTS

Fig. 4-3 Fault Tree – Total Vehicle

- No rpm change
- Erratic rpm
- Control lag
- Disconnection
- Oscillations

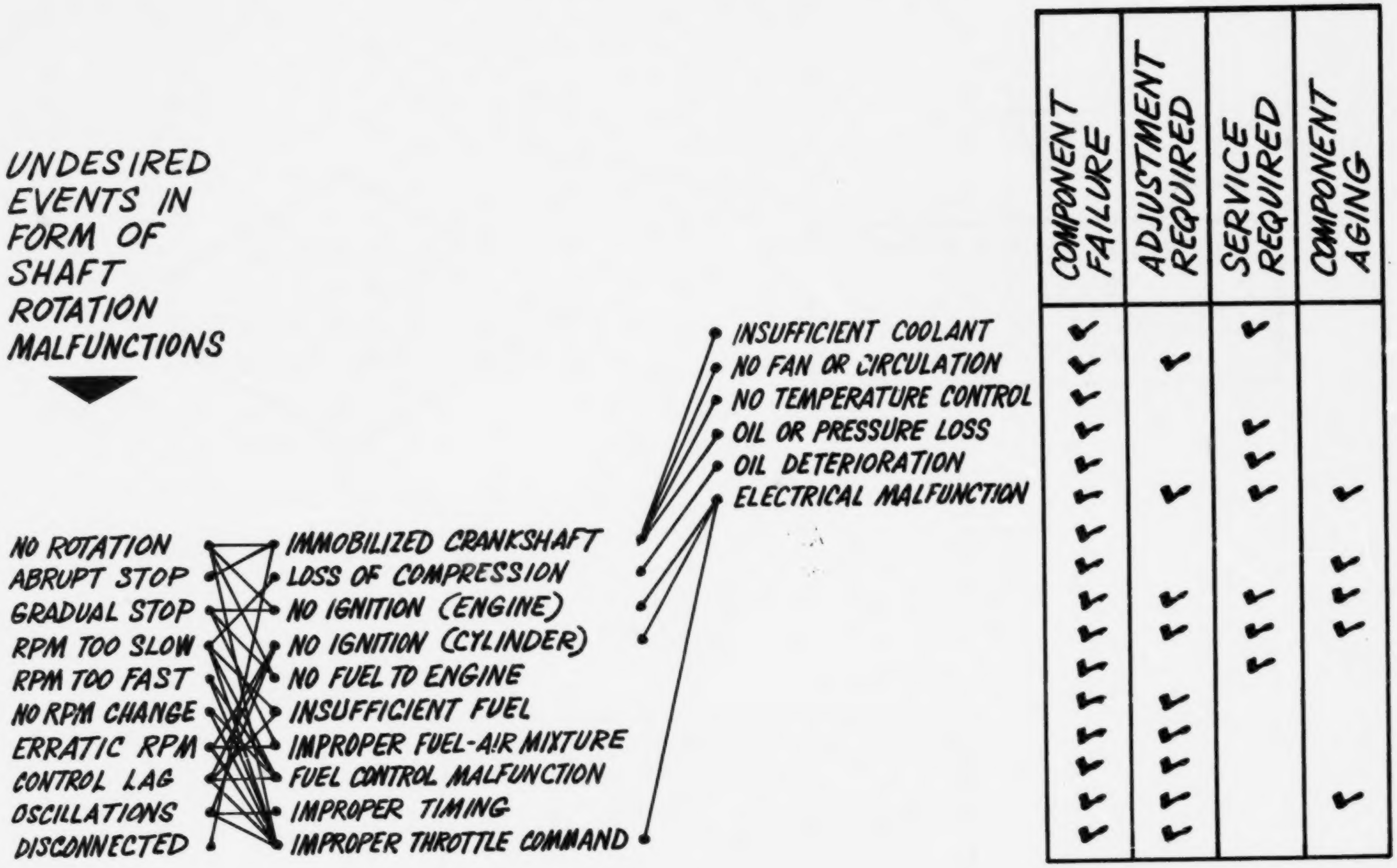
Inadequate functioning of power shafts and minor parts can form safety hazards by producing drive modes which are incompatible with the operational situation.

The engine is the system component for which the most certain and detailed knowledge is available. Figure 4-4 represents a fault tree approach to detail problems, simplified and presented in matrix form. From this figure, a fault path leading to engine shaft malfunctions and then to undesired events within the hybrid system can be readily traced. As transmission subsystems and details are selected, similar fault analysis can be made.

POSSIBILITY OF ACHIEVING ACCEPTABLE SAFETY

During the time frame under consideration, an average of 100 million highway vehicles will accumulate a trillion vehicle-miles per year within the United States. At present, there are approximately 50,000 fatalities per year, or one fatality every 20 million vehicle-miles. For sake of discussion, it may be assumed that all vehicles will be flywheel hybrids in the not too distant future. Thus, using a didactic, but reasonable, goal of limiting flywheel-caused fatalities to 10 or less per year, the resulting allowable incidence of fatalities attributable solely to flywheels would be approximately once every 100 billion vehicle miles. (See Fig. 4-5.)

As indicated in Fig. 4-6, the 10 or less annual fatal events related to the flywheel may occur in several modes. The type of failure judged to be most significant was the uncontained flywheel disintegration which, in turn, became the basis of estimating the degree of reliability required for the system components. (See Fig. 4-7.)


UNDESIRED EVENTS IN FORM OF SHAFT ROTATION MALFUNCTIONS
NO ROTATION
ABRUPT STOP
GRADUAL STOP
RPM TOO SLOW
RPM TOO FAST
NO RPM CHANGE
ERRATIC RPM
CONTROL LAG
OSCILLATIONS
DISCONNECTED
IMMOBILIZED CRANKSHAFT
LOSS OF COMPRESSION
NO IGNITION (ENGINE)
NO IGNITION (CYLINDER)
NO FUEL TO ENGINE
INSUFFICIENT FUEL
IMPROPER FUEL-AIR MIXTURE
FUEL CONTROL MALFUNCTION
IMPROPER TIMING
IMPROPER THROTTLE COMMAND
INSUFFICIENT COOLANT
NO FAN OR CIRCULATION
NO TEMPERATURE CONTROL
OIL OR PRESSURE LOSS
OIL DETERIORATION
ELECTRICAL MALFUNCTION

	COMPONENT FAILURE	ADJUSTMENT REQUIRED	SERVICE REQUIRED	COMPONENT AGING
INSUFFICIENT COOLANT	✓		✓	
NO FAN OR CIRCULATION	✓	✓		
NO TEMPERATURE CONTROL	✓			
OIL OR PRESSURE LOSS	✓		✓	
OIL DETERIORATION	✓		✓	
ELECTRICAL MALFUNCTION	✓	✓	✓	✓
IMMOBILIZED CRANKSHAFT	✓			
LOSS OF COMPRESSION	✓			✓
NO IGNITION (ENGINE)	✓	✓	✓	✓
NO IGNITION (CYLINDER)	✓	✓	✓	✓
NO FUEL TO ENGINE	✓		✓	
INSUFFICIENT FUEL	✓	✓		
IMPROPER FUEL-AIR MIXTURE	✓	✓		
FUEL CONTROL MALFUNCTION	✓	✓		
IMPROPER TIMING	✓	✓		✓
IMPROPER THROTTLE COMMAND	✓	✓		

Fig. 4-4 Engine System Fault Matrix

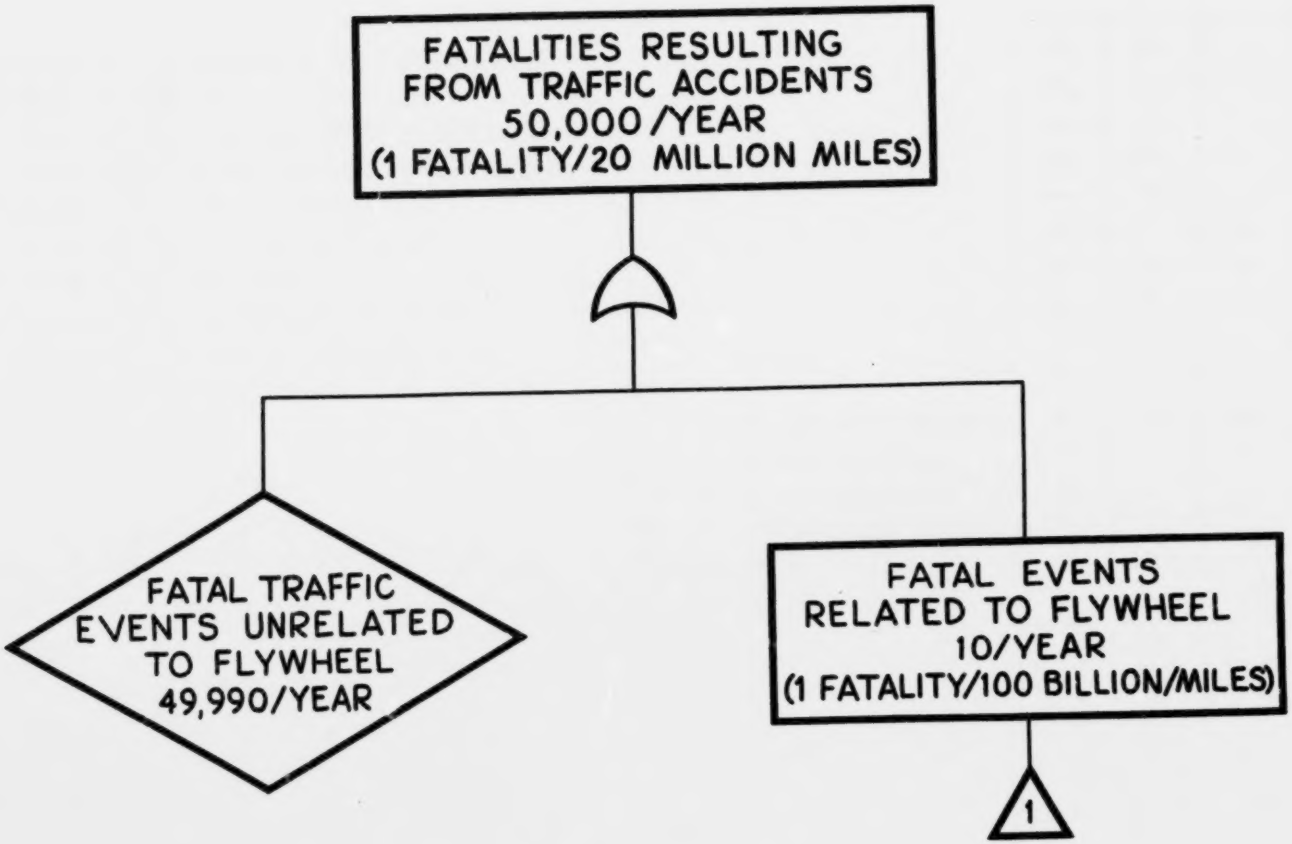

FATALITIES RESULTING
FROM TRAFFIC ACCIDENTS
50,000 /YEAR
(1 FATALITY/20 MILLION MILES)
FATAL TRAFFIC
EVENTS UNRELATED
TO FLYWHEEL
49,990/YEAR
FATAL EVENTS
RELATED TO FLYWHEEL
10/YEAR
(1 FATALITY/100 BILLION/MILES)
1

Fig. 4-5 Suggested Flywheel Safety Goal

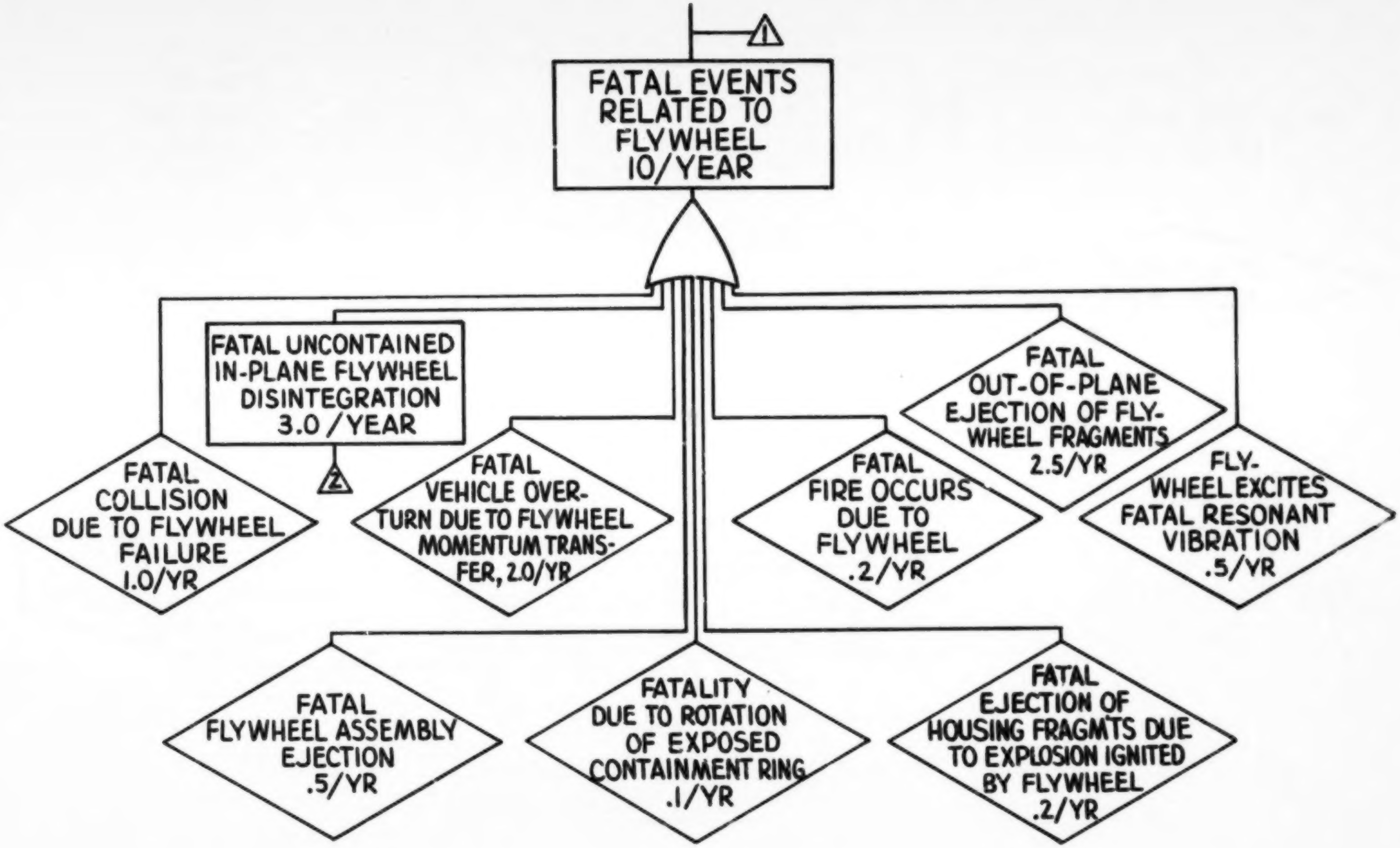

1
FATAL EVENTS RELATED TO FLYWHEEL 10/YEAR
FATAL UNCONTAINED IN-PLANE FLYWHEEL DISINTEGRATION 3.0/YEAR
2
FATAL COLLISION DUE TO FLYWHEEL FAILURE 1.0/YR
FATAL VEHICLE OVER-TURN DUE TO FLYWHEEL MOMENTUM TRANS-FER, 2.0/YR
FATAL FIRE OCCURS DUE TO FLYWHEEL .2/YR
FATAL OUT-OF-PLANE EJECTION OF FLY-WHEEL FRAGMENTS 2.5/YR
FLY-WHEEL EXCITES FATAL RESONANT VIBRATION .5/YR
FATAL FLYWHEEL ASSEMBLY EJECTION .5/YR
FATALITY DUE TO ROTATION OF EXPOSED CONTAINMENT RING .1/YR
FATAL EJECTION OF HOUSING FRAGM'TS DUE TO EXPLOSION IGNITED BY FLYWHEEL .2/YR

Fig. 4-6 Relative Concern About Failure Modes

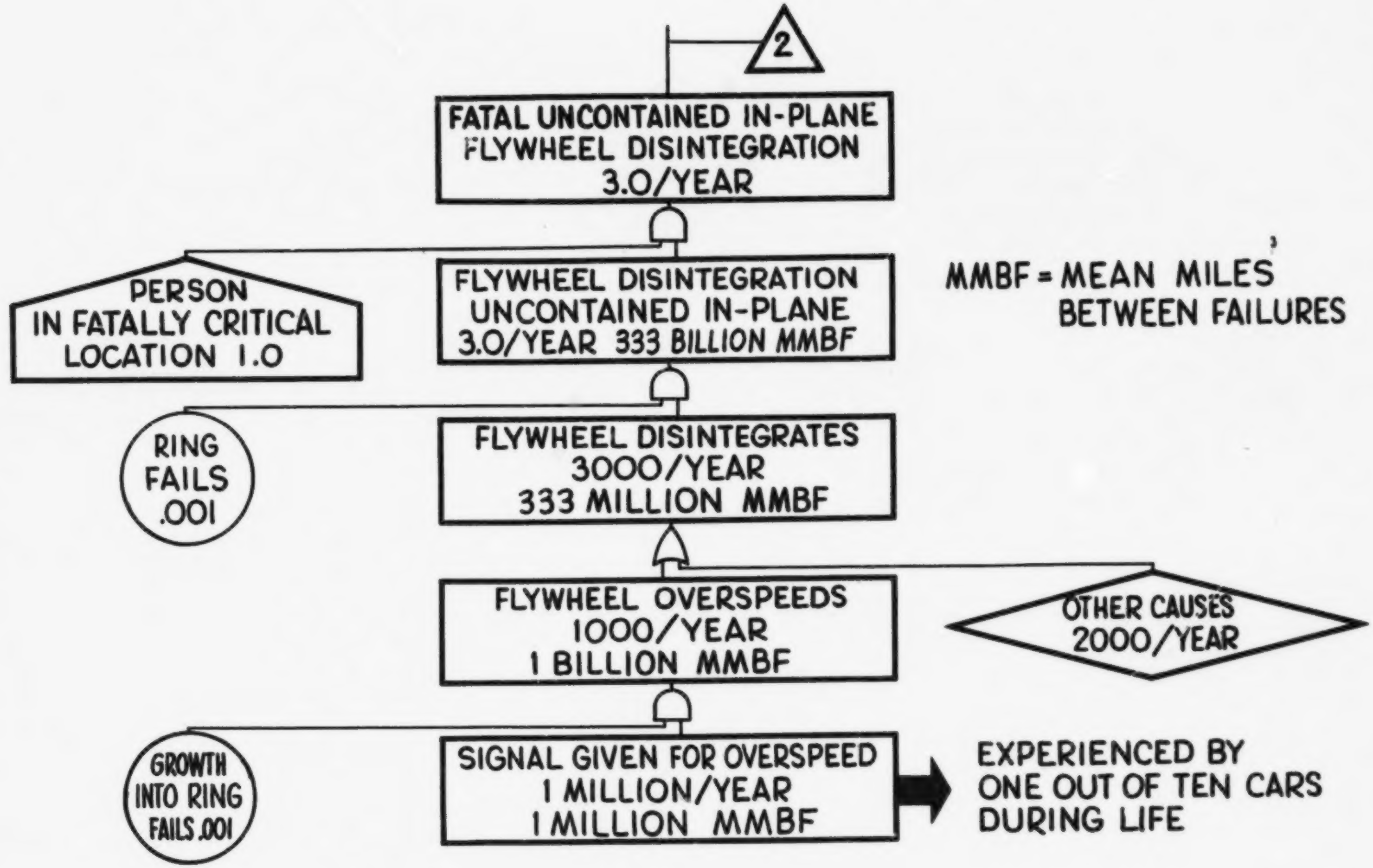

2
FATAL UNCONTAINED IN-PLANE FLYWHEEL DISINTEGRATION 3.0/YEAR
PERSON IN FATALLY CRITICAL LOCATION 1.0
FLYWHEEL DISINTEGRATION UNCONTAINED IN-PLANE 3.0/YEAR 333 BILLION MMBF
MMBF = MEAN MILES BETWEEN FAILURES
RING FAILS .001
FLYWHEEL DISINTEGRATES 3000/YEAR 333 MILLION MMBF
FLYWHEEL OVERSPEEDS 1000/YEAR 1 BILLION MMBF
OTHER CAUSES 2000/YEAR
GROWTH INTO RING FAILS .001
SIGNAL GIVEN FOR OVERSPEED 1 MILLION/YEAR 1 MILLION MMBF
EXPERIENCED BY ONE OUT OF TEN CARS DURING LIFE

Fig. 4-7 Degree of Reliability Required

It will be assumed that a flywheel disintegration not contained in-plane will result in one fatality on the average. The containment ring in failing will absorb a large percentage of the energy stored in the flywheel. Furthermore, the plane of disintegration may not be aligned with potential victims. Even in the plane of disintegration, lethal fragments will separate with distance, thus allowing space in which people can survive.

Non-fatal injuries are not considered in this aspect of the evaluation. However, the possibility of multiple fatalities including fatalities in adjacent vehicles must be considered. Thus, one fatality per flywheel disintegration which is not contained in-plane is assumed.

The containment ring serves as a safety device in two modes – burst containment and burst prevention – since a normal flywheel will yield and grow into the ring before fracturing. The chances of the flywheel bursting can be held to 1 in 1,000 and, if the flywheel does fracture, the chances of it not being contained can again be held to 1 in 1,000. Once a containment design is established, this type of reliability is to be expected. The probabilities derived in detail in Figs. 4-6 and 4-7 show that conditions for flywheel overspeed could be allowed to occur in the United States one million times each year within the rigorous safety goal established. This, in turn, represents 1 million MMBF.* In other words, conditions for flywheel failure could happen to 1 out of every 10 cars at some time during the expected lifetime of the car. This requirement is not too difficult. Uncontained flywheel disintegration is, of course, only one single vertical probe in the fault tree. It was chosen because the problem is a familiar one which has been emphasized in the study.

---

*Mean miles between failures.

RELATIVE SAFETY OF ALTERNATIVE DESIGNS

It has been necessary to confine the detailed examination of fault tree paths to an immediate area of interest. This area pertains directly to the flywheel and excludes internal analyses of other new components peculiar to the hybrid system, whether or not they affect the safe operation of the flywheel. Although the system controls and the transmission can cause malfunction of the flywheel, sufficient details were not available to extend the fault tree downward into these areas. Vehicle safety not related to the hybrid system was ignored in the analyses. (See Fig. 4-8.)

The use of the fault tree provides a method of quantifying the relative safety of two or more design candidates, as shown in Fig. 4-9. An arbitrary hazard index number can be assigned to one of the candidate configurations and distributed downward within a pertinent portion of the fault tree as in the case of the vertical probe previously mentioned. Each assigned number can then be appraised in relation to characteristics exhibited by competing configurations and a relative value assigned. With these new values, the fault tree can be quantified for other configurations, building upward to produce a top hazard index number for the top undesired event which can then be compared to the top hazard index number assigned to the first candidate. In this manner, it is possible in initial design phases to use the fault tree to establish the relative safety of alternative designs. This information can then be compared with cost, weight, and performance estimates to form tradeoff studies. An illustration of how this safety determination could be accomplished involves the case of fatalities due to flywheel failure caused by impact. (See Fig. 4-10.)

The occurrence of such fatalities is dependent upon several factors. The first is the alignment of the flywheel plane of lethality with potential victims. (See Fig. 4-11.) The mode of collision is to be considered in respect to direction and severity of impact, and the probability of occurrence. The penetrability of the installation location must be evaluated. The flywheel configuration will present differing target areas and impact strength in differing orientations. These combinations can be described by the fault tree.

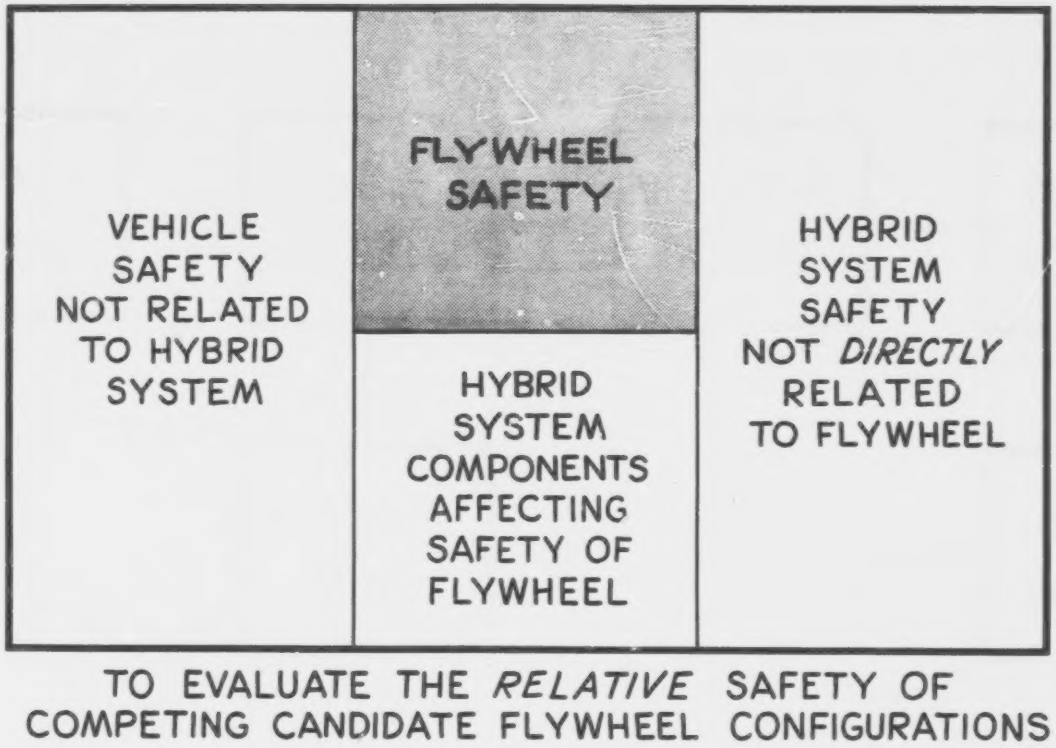

VEHICLE SAFETY NOT RELATED TO HYBRID SYSTEM
FLYWHEEL SAFETY
HYBRID SYSTEM COMPONENTS AFFECTING SAFETY OF FLYWHEEL
HYBRID SYSTEM SAFETY NOT *DIRECTLY* RELATED TO FLYWHEEL
TO EVALUATE THE *RELATIVE* SAFETY OF COMPETING CANDIDATE FLYWHEEL CONFIGURATIONS

Fig. 4-8 Immediate Area of Interest

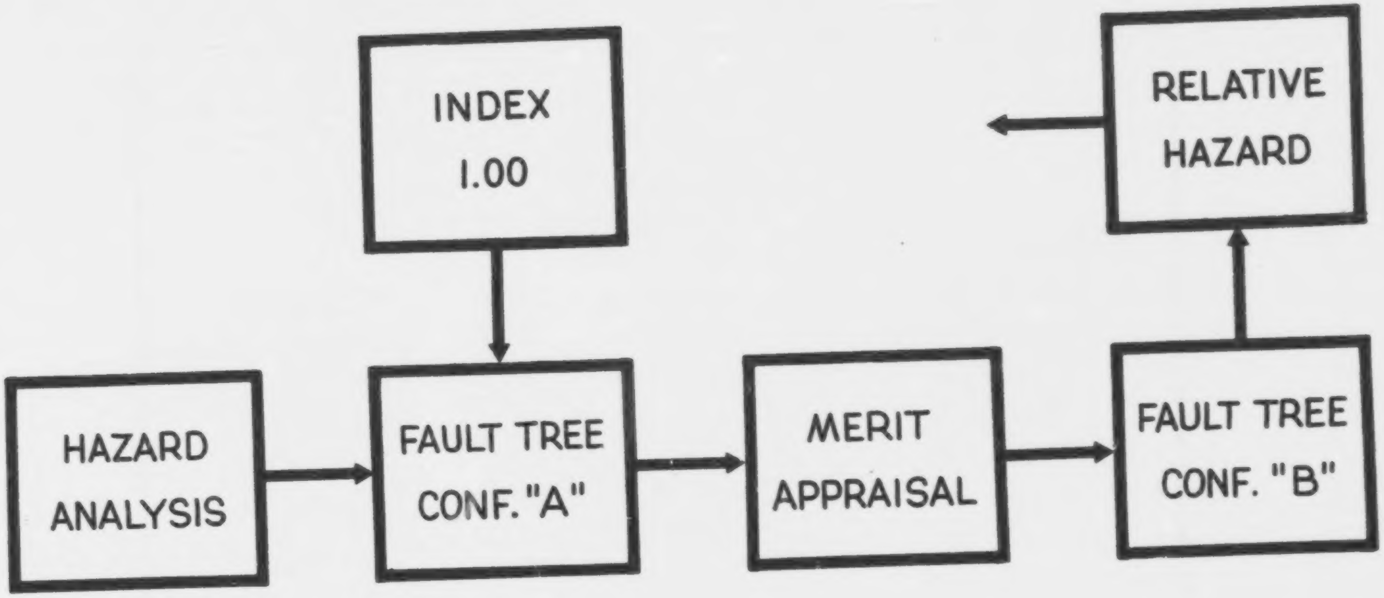

HAZARD
ANALYSIS
INDEX
1.00
FAULT TREE
CONF. "A"
MERIT
APPRAISAL
FAULT TREE
CONF. "B"
RELATIVE
HAZARD

Fig. 4-9 Relative Safety Evaluation Methodology

$$A = B \times [(D \times E \times F \times G \times H) + (J \times K \times L \times M \times N) + (P \times Q \times R \times S \times T) + (V \times W \times X \times Y \times Z)]$$

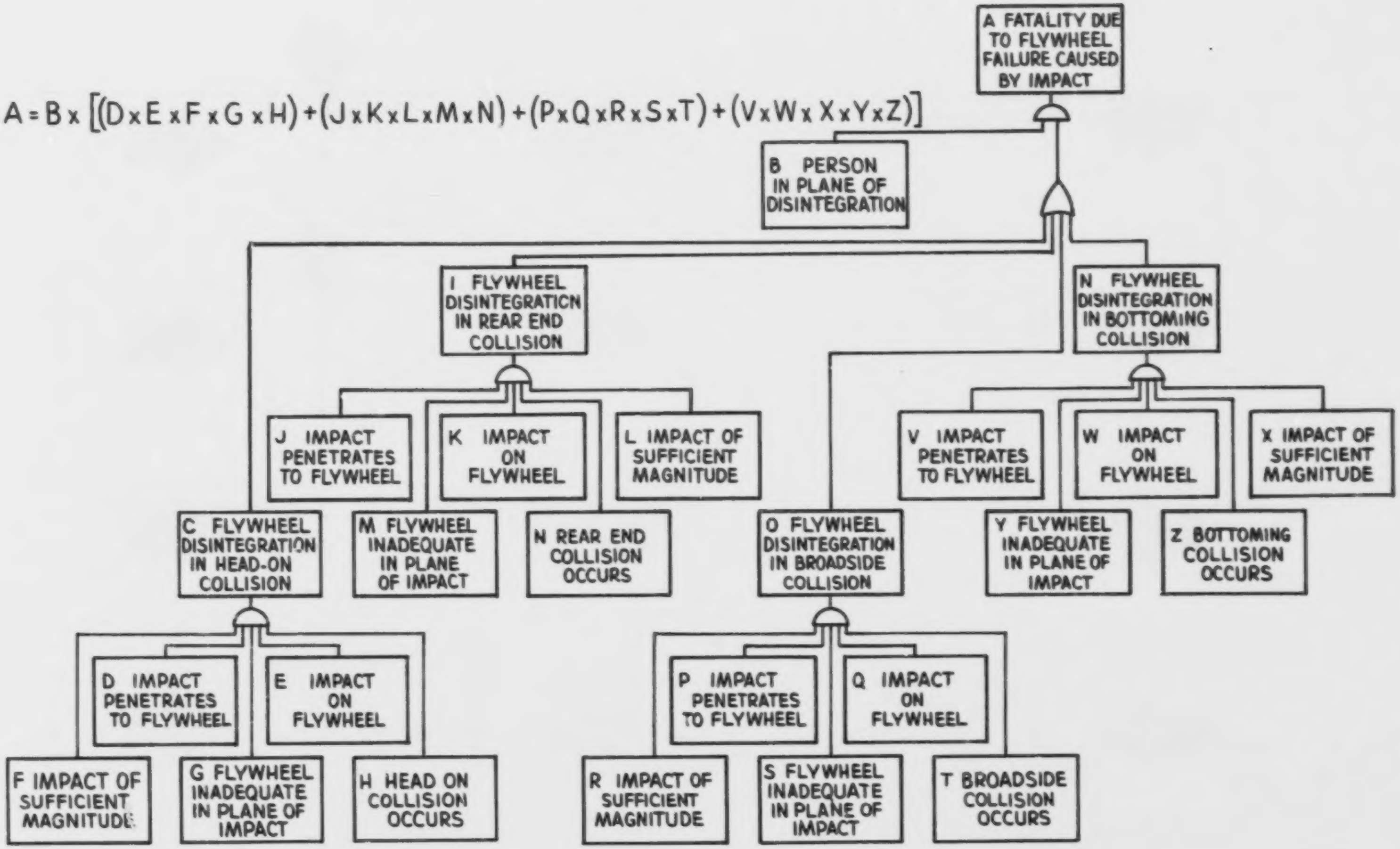

A FATALITY DUE TO FLYWHEEL FAILURE CAUSED BY IMPACT
B PERSON IN PLANE OF DISINTEGRATION
I FLYWHEEL DISINTEGRATION IN REAR END COLLISION
N FLYWHEEL DISINTEGRATION IN BOTTOMING COLLISION
J IMPACT PENETRATES TO FLYWHEEL
K IMPACT ON FLYWHEEL
L IMPACT OF SUFFICIENT MAGNITUDE
V IMPACT PENETRATES TO FLYWHEEL
W IMPACT ON FLYWHEEL
X IMPACT OF SUFFICIENT MAGNITUDE
C FLYWHEEL DISINTEGRATION IN HEAD-ON COLLISION
M FLYWHEEL INADEQUATE IN PLANE OF IMPACT
N REAR END COLLISION OCCURS
O FLYWHEEL DISINTEGRATION IN BROADSIDE COLLISION
Y FLYWHEEL INADEQUATE IN PLANE OF IMPACT
Z BOTTOMING COLLISION OCCURS
D IMPACT PENETRATES TO FLYWHEEL
E IMPACT ON FLYWHEEL
P IMPACT PENETRATES TO FLYWHEEL
Q IMPACT ON FLYWHEEL
F IMPACT OF SUFFICIENT MAGNITUDE
G FLYWHEEL INADEQUATE IN PLANE OF IMPACT
H HEAD ON COLLISION OCCURS
R IMPACT OF SUFFICIENT MAGNITUDE
S FLYWHEEL INADEQUATE IN PLANE OF IMPACT
T BROADSIDE COLLISION OCCURS

Fig. 4-10 Collision Impact

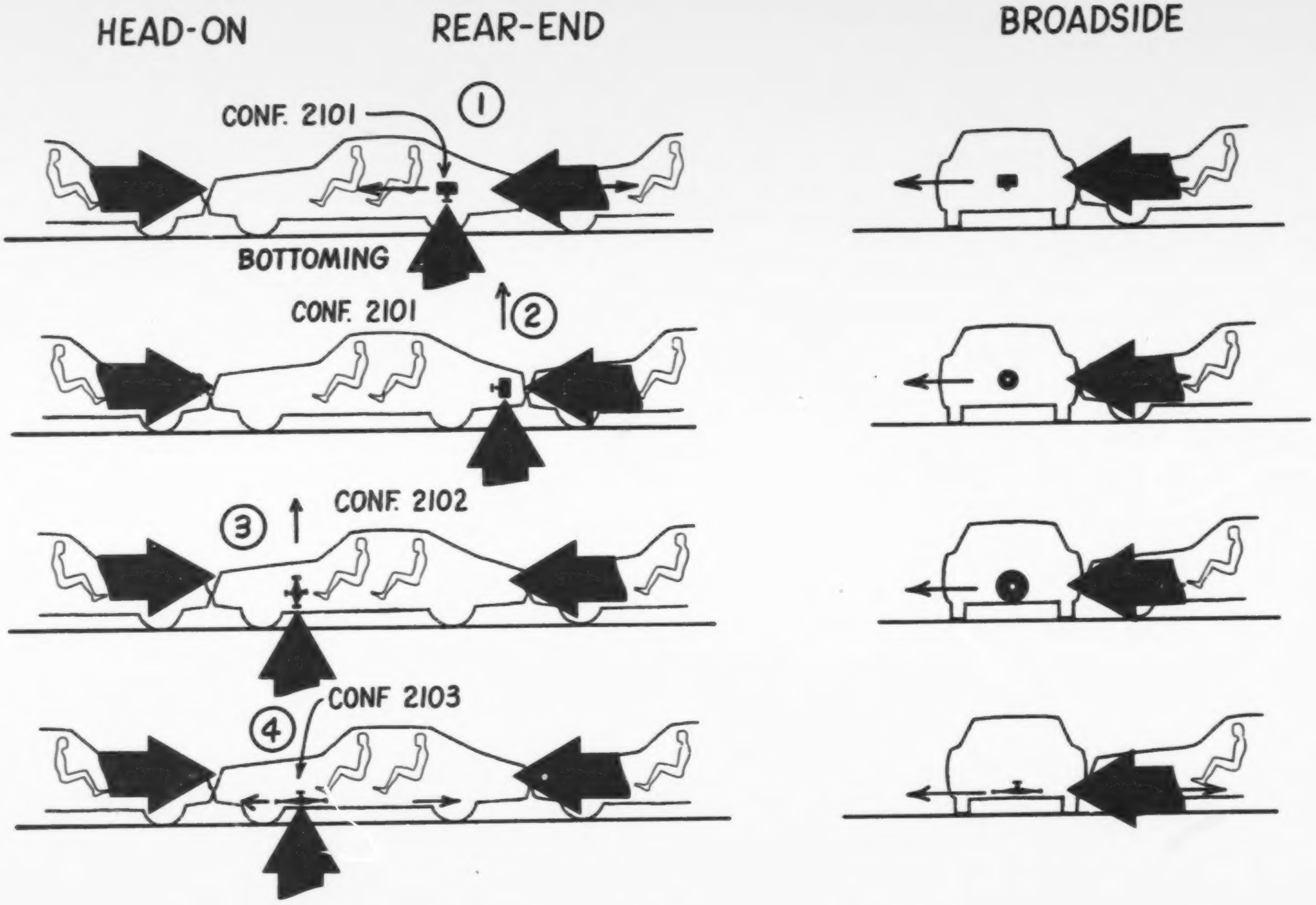

HEAD-ON
REAR-END
BROADSIDE
CONF. 2101
①
BOTTOMING
CONF. 2101
②
③
CONF. 2102
④
CONF 2103

Fig. 4-11 Collision Vulnerability Analysis

It is of interest that, using the total kinetic energy approach, high vehicle velocities are obtained only when flywheel stored energy is low. This phenomenon is of significance in both the case of single-car collisions and the case of head-on collisions between two speeding cars.

There is a point at which all persons in or around the subject vehicle (or vehicles) are presumed not to be able to survive. The criteria used in Federal safety car programs indicate that this might be around the area of head-on closure speeds in excess of 70 mph or hitting brick walls at speeds in excess of 50 mph (Fig. 4-12). If a collision is so severe, for example, that the occupants of all cars involved (and proximate bystanders) are killed, the flywheel does not present an additional hazard. It is to be assumed, in such a collision, that a large portion of the energy stored in the flywheel will be dissipated even if the containment ring were to burst, thus rendering remote secondary effects unlikely. As flywheel installations are buried deeper into the vehicle, the collision impact must be more and more severe to penetrate all the way to the flywheel with sufficient energy remaining to cause flywheel disintegration. In the case of a speeding car, the flywheel is probably at low energy.

The durability of the flywheel when hit is dependent upon its axial orientation, and different flywheel configurations offer varying susceptibility to impact damage (See Fig. 4-13). The characteristics of flywheels which affect safety include maximum stress level, diameter-to-width ratio, peripheral speed, maximum g loading, section undercutting, heat-sink mass, cantilever, target area, and rim width.

A matrix (Fig. 4-14) has been established to evaluate various combinations of orientation, location, and configuration. The candidate arrangements designated as I and II are seen to be superior in terms of relative hazard, but involve severe space problems. During the course of the study, consideration was given to candidate arrangements III, IV, V, and X. The lowest hazard rating of these is that of candidate IV. Although oriented in the most lethal plane, it has the lowest vulnerability of all. Candidates III and V have the least dangerous orientations, but are more vulnerable. Candidate X is the most hazardous of those seriously considered; it is most vulnerable to bottoming.

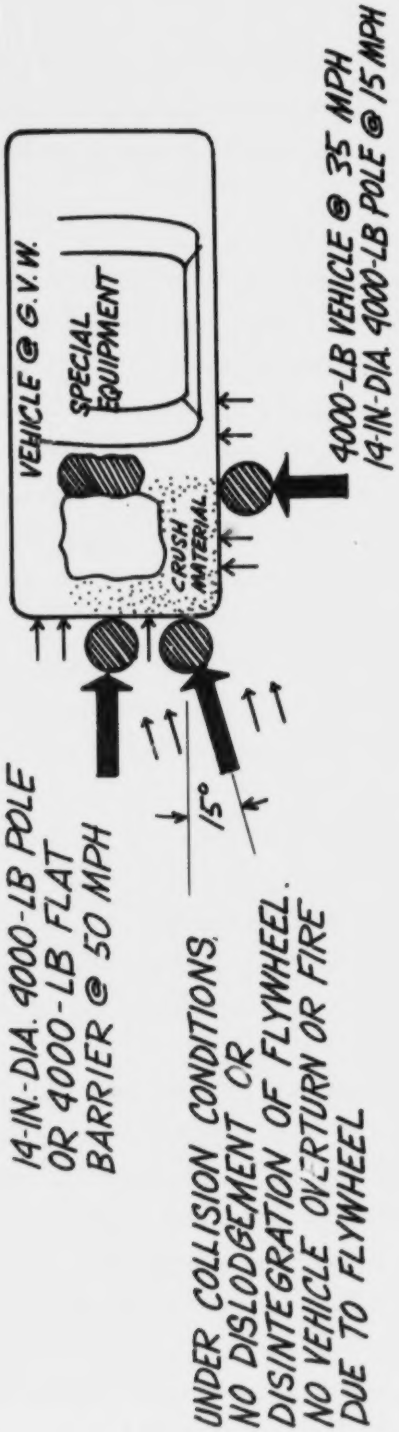
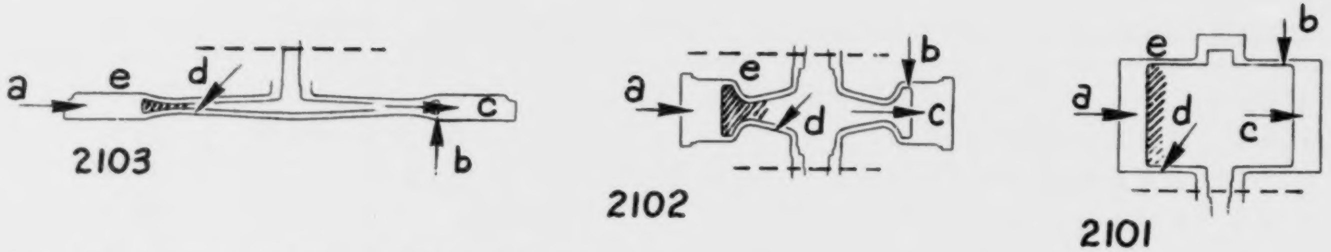

VEHICLE @ G.V.W.
SPECIAL EQUIPMENT
CRUSH MATERIAL
4000-LB VEHICLE @ 35 MPH
14-IN-DIA. 4000-LB POLE @ 15 MPH
14-IN.-DIA. 4000-LB POLE OR 4000-LB FLAT BARRIER @ 50 MPH
15°
UNDER COLLISION CONDITIONS, NO DISLODGEMENT OR DISINTEGRATION OF FLYWHEEL. NO VEHICLE OVERTURN OR FIRE DUE TO FLYWHEEL

Fig. 4-12 Design Safety Criteria



a - IN-PLANE IMPACT VULNERABILITY

HOUSING RADIUS/WIDTH ; FLYWHEEL RADIUS/RIM WIDTH (℄ MIN. WIDTH)
UNDERCUT ANGLE ; CANTILEVER ; PERIPHERAL SPEED

b - OUT-OF-PLANE IMPACT VULNERABILITY

HOUSING RADIUS/WIDTH ; FLYWHEEL RADIUS/ROOT WIDTH (℄ MIN. WIDTH)
PERIPHERAL SPEED ; CANTILEVER

c - IN-PLANE CONTAINMENT

PERIPHERAL SPEED ; RIM WIDTH ; RING WEIGHT

d - OUT-OF-PLANE CONTAINMENT

FLYWHEEL RADIUS/RIM WIDTH ; UNDERCUT ANGLE PERIPHERAL SPEED ;
SIDEWALL WEIGHT

e - FRICTION HEATING

PERIPHERAL SPEED ; RIM WIDTH ; UNDERCUT ANGLE

Fig. 4-13 Flywheel Configuration Evaluation

$$A = B \times [(D \times E \times F \times G \times H) + (J \times K \times L \times M \times N) + (P \times Q \times R \times S \times T) + (V \times W \times X \times Y \times Z)]$$

				HEAD-ON						REAR-END						BROADSIDE						BOTTOMING					
		CANDIDATE HAZARD	PLANE LETHALITY	VULNERABILITY	PENETRABILITY	TARGET AREA	SEVERITY	FREQUENCY	CONFIGURATION	VULNERABILITY	PENETRABILITY	TARGET AREA	SEVERITY	FREQUENCY	CONFIGURATION	VULNERABILITY	PENETRABILITY	TARGET AREA	SEVERITY	FREQUENCY	CONFIGURATION	VULNERABILITY	PENETRABILITY	TARGET AREA	SEVERITY	FREQUENCY	CONFIGURATION
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
I	2101FL	942	2	270	3	3	5	2	3	135	1	3	3	5	3	54	3	2	3	3	1	12	3	2	1	2	1
II	2101FV	762	3	80	4	2	5	2	1	30	1	2	3	5	1	54	3	2	3	3	1	90	5	3	1	2	3
III	2101RL	1842	2	180	2	3	5	2	3	675	5	3	3	5	3	54	3	2	3	3	1	12	3	2	1	2	1
IV	2101RV	910	5	20	1	2	5	2	1	90	3	2	3	5	1	54	3	2	3	3	1	18	1	3	1	2	3
V	2102FL	1836	2	480	3	4	5	2	4	240	1	4	3	5	4	162	3	3	3	3	2	36	3	3	1	2	2
VI	2102FV	1956	3	240	4	3	5	2	2	90	1	3	3	5	2	162	3	3	3	3	2	160	5	4	1	2	4
VII	2102RL	3436	2	320	2	4	5	2	4	1200	5	4	3	5	4	162	3	3	3	3	2	36	3	3	1	2	2
VIII	2102RV	2620	5	60	1	3	5	2	2	270	3	3	3	5	2	162	3	3	3	3	2	32	1	4	1	2	4
IX	2103FL	3006	2	750	3	5	5	2	5	375	1	5	3	5	5	324	3	4	3	3	3	54	3	3	1	2	3
X	2103FV	3207	3	360	4	3	5	2	3	135	1	3	3	5	3	324	3	4	3	3	3	250	5	5	1	2	5
XI	2103RL	14506	2	5000	2	5	5	2	5	1875	5	5	3	5	5	324	3	4	3	3	3	54	3	3	1	2	3
XII	2103RV	4345	5	90	1	3	5	2	3	405	3	3	3	5	3	324	3	4	3	3	3	50	1	5	1	2	3

FL = FRONT LONGL.; FV = FRONT VERTICAL; RL = REAR LONGL.; RV = REAR VERTICAL

Fig. 4-14 Candidate Merit Appraisal

A low hazard rating alone cannot select the "optimum" candidate; cost, weight, and performance tradeoffs must be considered.

The above analyses have been concerned with structural failure of the flywheel due to overspeed and accident impact. As indicated in Fig. 4-15, several other problems are of concern. One of these problems is that of momentum transfer from the flywheel into the vehicle with resulting hazards of instability, loss of control, and dislodgement, as shown in Fig. 4-16. In the course of the study, remedies have been suggested for each set of problems and hazards. These in turn can be used in establishing safety design requirements.

PROBLEMS	HAZARDS	REMEDIES
MOMENTUM TRANSFER	•ROTATING RING •DISLODGED ASSY •CONTROL INSTABILITY •OVERTURN	•GUARD •BREAKAWAY BEARINGS
CONTROL SYSTEM	•FLYWHEEL OVERSPEED	•QUALITY CONTROL •FACTORY SEALED •PERIODIC CHECK •HISTORY WARNING •RPM GOVERNING •REDUNDANCY •SYSTEM INTERLOCK
ACCIDENT IMPACT	•BURST FLYWHEEL •PROPELLED FRAGMENTS •EJECTED FLYWHEEL •VEHICLE OVERTURN •CONTROL INSTABILITY •FIRE	CONTAINMENT RING FUNCTIONS AS IMPACT SHIELDING
MANUFACTURING	•NOTCHED (OCCLUSIONS) •UNBALANCED •LOW HEAT TREAT •UNPROTECTED •OUT OF ADJUSTMENT •CONTAMINATED	•MECHANIC TRAINING •PRECISION TOOLING •PROCEDURES •SUPERVISION •INSPECTION •PACKAGING

PROBLEMS	HAZARDS	REMEDIES
STRUCTURAL FAILURE	•IN-PLANE DISINTEGRATION •OUT-OF-PLANE MOVEMENT •GROWTH INTO RING •MOMENTUM TRANSFER •HEATING	•CONTAINMENT RING •CLOSE CLEARANCES BREAKAWAY BEARINGS
MAINTENANCE	•NOTCHING •SPALLING •ANNEALING •CORROSION •ABRASION •FATIGUING	•UNIT REPLACEMENT •"TINKER PROOFING"
VACUUM SEAL	•CHEMICAL EXPLOSION FRICTION IGNITES OIL MIST & AIR DRAWN INTO CHAMBER FRAGMENTING HOUSING	•HEAT SINK •BLOWOUT PATCH
	•FLYWHEEL DETERIORATION WITH SEAL LEAK MOISTURE CORRODES, ABRASIVES SANDBLAST & AIR OVERHEATS FLYWHEEL	•NON-CORROSIVE FINISH •CHECK VALVES •HEAT SINK

Fig. 4-15 Suggested Design Requirements

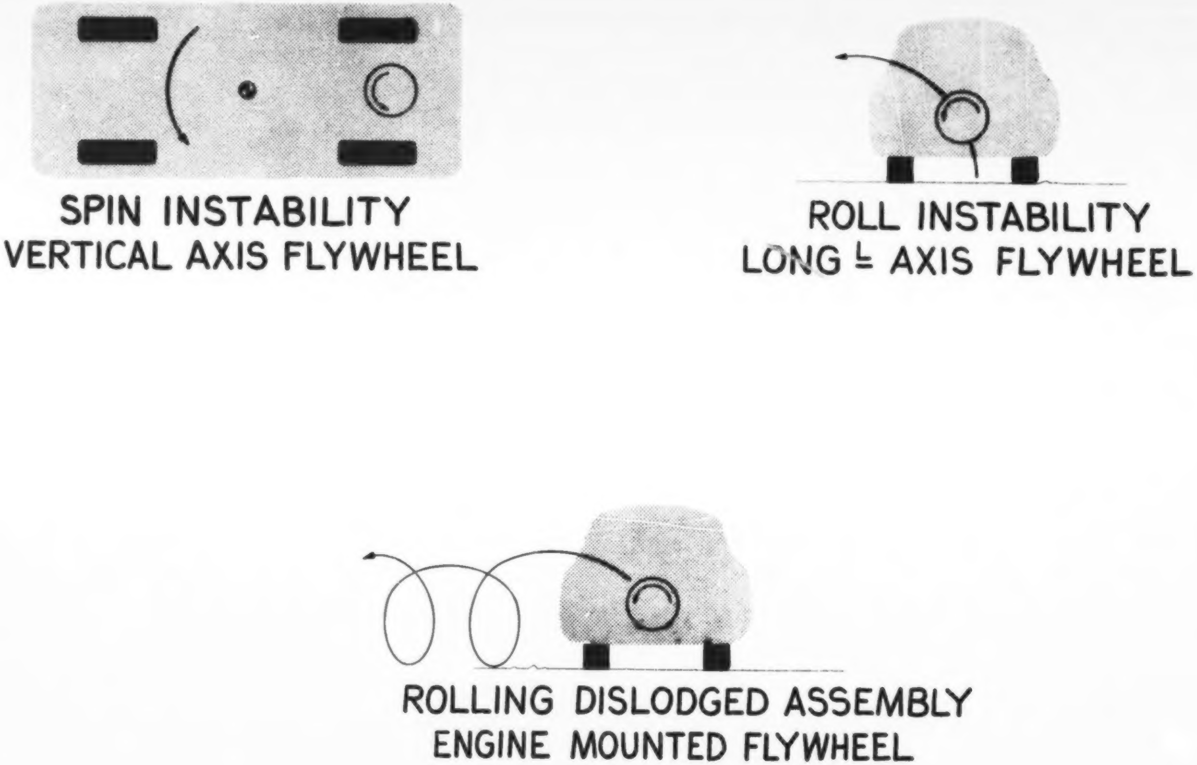

SPIN INSTABILITY
VERTICAL AXIS FLYWHEEL
ROLL INSTABILITY
LONG ℄ AXIS FLYWHEEL
ROLLING DISLODGED ASSEMBLY
ENGINE MOUNTED FLYWHEEL

Fig. 4-16 Vehicle Instability Through Momentum Transfer

Section 5
FLYWHEEL ANCILLARY EQUIPMENT DESIGN STUDY

Design studies of ancillary equipment essential for efficient high speed flywheel performance were conducted. The major components for study include bearings, rotary seals, and vacuum pumps. Component requirements and availability were established to optimize component selection and the overall design of the flywheel system.

Since the flywheel system must couple with a power transmission drive system in an automobile for the general public, certain goals were maintained throughout the studies. These included the following:

- Low cost
- Reliability
- Safety
- Maintainability

BEARINGS

The specific requirements established for the flywheel support bearings are as follows:

- Bearing Size
  - Shaft diameter 30 mm (min.)
  - Outer diameter Open
  - Width Open
- Life Requirement – 2,500 hr (L_{10} life)* min., operation per load schedule in Table 5-1
- Dynamic Drag Torque – 0.28 in. lb, max. at 24,000 rpm
- Load and Speed Capacities – per Table 5-1

---

*L_{10} bearing life is defined by AFBMA as the number of hours (at some given constant speed) that 90 percent of a group of bearings will complete or exceed before the first evidence of fatigue develops.

● Operating Environment – Automotive Transmission	
– Operating temperature	180° to 300°F
– Soak temperatures	-25° to 130°F
● Lubrication	
– Type of oil	SAE 10-30 or Type A transmission
– Method of application	Oil jet
– Flow rate	To be specified
– Oil inlet temperature	180° ± 20°F

Supporting calculations for the loads shown in Table 5-1 are given in Appendix G.

There are two basic types of bearings – sliding and rolling. The sliding bearings are usually a cylindrical journal type or flat thrust types with either boundary or full film lubrication. The crankshaft bearing used on most automobile engines is of this type. The second type is the rolling element bearing where the load is carried by balls, rollers, needle rollers, or tapered rollers.

Front wheel bearings of an automobile are of the rolling element type. Table 5-2 is a brief summary of characteristics of the two main types of bearings. Advantages and disadvantages are tabulated as applied to the flywheel support bearings.

The bearing shaft diameter specified in the requirements is based principally on the minimum diameter shaft that can be used and still maintain the critical speed of the flywheel above its rotational speed.

Operation above critical speed changes the spin axis from the bearing axis to the center of gravity of the flywheel. For example, a flywheel with an imbalance of 0.001-in. displacement, will have its center of mass 0.001 in. from the bearing axis. At speeds below critical, the flywheel center of mass will orbit around the bearing spin axis causing a rotating centrifugal force on the bearings.

Table 5-1
SUMMARY OF SPEED AND LOAD DATA

Type of Load	Period of Time (%)	Speed (rpm)	Bearing Loads (lb)(a)(b)
Radial Loads	2	24,000	262
	3	24,000	262
	5	22,000	220
	15	20,000	186
	35	18,000	147
	20	14,000	89
	10	12,000	65
	10	8,000	30
	100		

Type of Load	Rate of Application of Load (cyc/hr)	Duration of Loads (sec)	Loads on Bearing (lb)(c)
Gyroscopically Induced Bearing Loads	0.001	2.0	1,800
	0.0015	2.0	1,400
	0.002	1.5	1,000
	0.003	1.5	800
	0.005	1.0	600
	30.0	2.0	300
	100.0	2.5	200
	500.0	0.2	100
	12,000.0	0.1	40

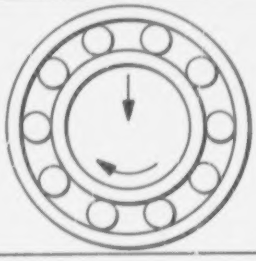
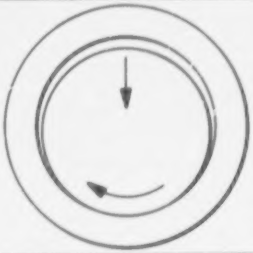
(a) All loads in this table are radial rotating loads with inner race rotating and outer race stationary; loads are applied at center of bearings; and inner and outer races are all to be clamped.

(b) Additional radial loads are steady 45 lb downward loads at all times (one-half flywheel weight).

(c) Radial loads to be superimposed on steady loads above; loads applied at random with respect to shaft speeds.

Table 5-2

CHARACTERISTICS OF ROLLING AND SLIDING BEARINGS[a]

		
Characteristic	**Rolling**	**Sliding**
Life	Limited by fatigue properties of bearing metal	Unlimited, except for cyclic loading
Load Cyclic	Good	Good
Starting	Excellent	Poor
Imbalance	Excellent	Good
Shock	Good	Fair
Emergency	Fair	Fair
Speed limited by:	Centrifugal loading Material surface speeds Ball control Ball skidding	Turbulence Temperature rise
Starting friction	Good	Poor
Cost	Low for automotive mass production quantities	Very low in simple types or in mass production
Misalignment tolerance	Good – radial ball-bearing tolerates small tracking error	Fair
Noise	Good for preloaded bearings	Quiet
Damping	Good – preloaded bearings	Good
Low-temperature, starting	Good	Poor
Type of lubricant	Oil or grease	Oil, water, other liquids, grease, dry lubricants, air, or gas
Lubrication, quantity required	Very small, except where large amounts of heat must be removed	Large, except in low-speed boundary-lubrication types
Type of failure	Limited operation may continue after fatigue failure but not after lubricant failure	Often permits limited emergency operation after failure
Ease of replacement	Function of type of installation. Usually shaft need not be replaced	Function of design and installation Split bearings used in large machines
Drag torque	Good to excellent	Good to poor, limited by Turbulence Temperature rise

(a) Amended to specific flywheel application from Ref. 5-1.

The formula for centrifugal force is:

$$CF = mr\omega^2$$

where

CF = centrifugal force (lb)
m = mass ($\text{lb-sec}^2/\text{in.}$)
r = displacement of CG from spin axis (in.)
ω = rotational speed (rad/sec)

This centrifugal force is the major load on the bearings.

Figure 5-1 illustrates the imbalance plotted against rotational speeds generally applied to rotating components common to industry. An imbalance of 0.0002-in. displacement for the flywheel assembly is considered the practical limit for high speed mass production balancing equipment. The centrifugal force created by this imbalance is the steady rotating force imposed upon the bearings. (See Table 5-1.)

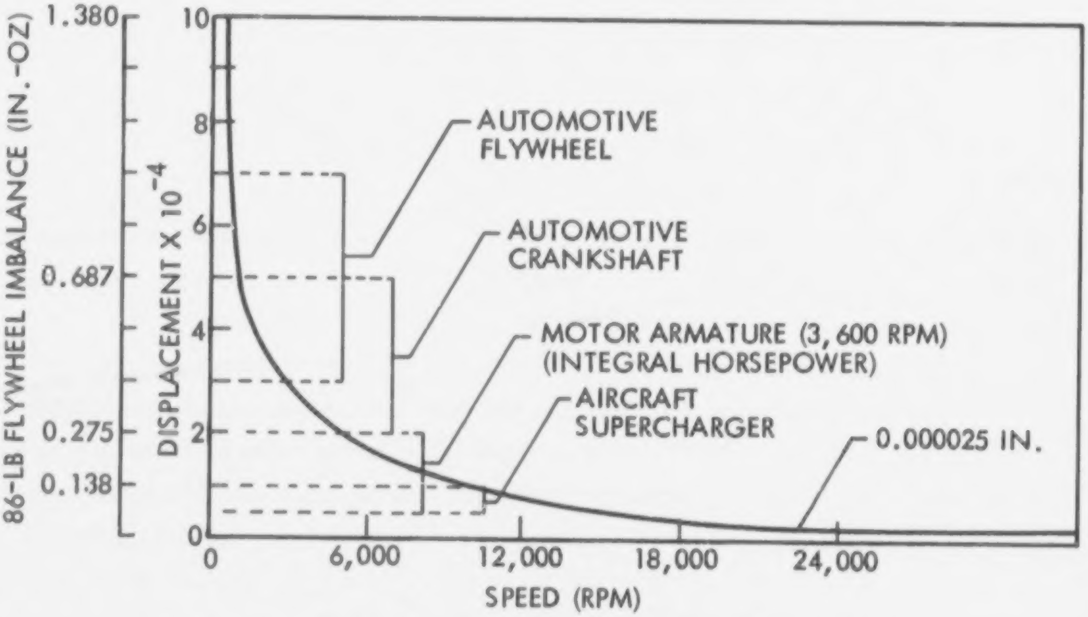


Fig. 5-1 Flywheel Imbalance Displacement Vs. Engine Speed

Tables 5-3 and 5-4 give various materials used for sliding bearings. Table 5-3 includes those materials used with "dry" bearings or, at least, where boundary lubrication exists. Table 5-4 is for full-film lubrication.

Boundary-lubricated bearing speed limits are commonly expressed in PV terms, that is, load on the projected area of the bearing in psi multiplied by the surface velocity in ft/min. Thus:

$$PV = p \cdot a \cdot v$$

where

p = material pressure limit (psi) (Table 5-3)
a = projected area (in.^{2})
v = surface velocity (ft/min)

Using the limits for porous bronze, which has the highest listed PV value,

p = 4,000 psi
a = 1.18^2 (ratio of diameter to length = 1)
v = $(1.18/12) \cdot 24{,}000 = 7{,}380$ ft/min
$PV = 4{,}000 \times 1.18^2 \times 7{,}380 = 4{,}120 \times 10^4$

This value for porous bronze far exceeds the 5×10^4 maximum limit expressed in the Table 5-3. For this application, boundary-lubrication sliding bearings may have adequate load capacity but fall far short in terms of speed requirement.

The bearing selection is thus between the full-film sliding bearing and the rolling element bearing. Although speed limits on these two bearing types are imposed by different mechanisms (Table 5-2) both have very high and approximately the same effective upper speed limits. Full-film sliding bearings have turbulence and temperature

Table 5-3

MATERIALS FOR SLEEVE BEARINGS[a]

Material	Maximum Load (psi)	Maximum Speed (ft/min)	PV Limit (psi, ft/min)	Maximum Operating Temp. (°F)	Cost[b] ($)
Porous Bronze	4,000	1,500	50,000	150	0.11
Porous Iron	8,000	800	50,000	150	0.09
Teflon Fabric	60,000	50	25,000	500	0.04
Phenolic	6,000	2,500	15,000	200	0.05
Wood	6,000	2,000	15,000	150	0.40
Carbon Graphite	600	2,500	10,000	750	0.39
Reinforced Teflon	2,500	2,500	10,000	500	0.45
Nylon	1,000	1,000	3,000	200	0.04
Delrin	1,000	1,000	3,000	180	0.03
Lexan	1,000	1,000	3,000	220	0.05
Teflon	500	100	1,000	500	1.00

(a) See Ref. 5-1.
(b) Cost figures are for a 1-in. sleeve bearing ordered in quantity.

Table 5-4

MATERIALS FOR OIL-FILM JOURNAL BEARINGS[a]

Material	Load-Carrying Capacity (psi)	Maximum Operating Temp. (°F)	Compatibility[b]	Conformability and Embeddability[b]	Corrosion Resistance[b]	Fatigue Strength[b]
Tin-Base Babbitt	800 to 1,500	300	1	1	1	5
Lead-Base Babbitt	800 to 1,200	300	1	1	3	5
Alkali-Hardened Lead	1,200 to 1,500	500	2	1	5	5
Cadmium Base	1,500 to 2,000	500	1	2	5	4
Copper-Lead	1,500 to 2 500	350	2	2	5	3
Tin Bronze	4,000	500+	5	5	2	1
Lead Bronze	3,000 to 4,000	450	3	4	4	2
Aluminum Alloy	4,000	250	4	3	1	2
Silver (Overplated)	4,000	500	2	3	1	1
Three-Component Bearings (Babbitt Surfaced)	2,000 to 4,000	225 to 300	1	2	2	2

(a) See Ref. 5-1.
(b) Numbers indicate material suitability, ranging from 1 (most) to 5 (least).

limits which hold the surface speeds to about 20,000 ft/min, and rolling element bearings have centrifugal loads, ball control, and ball skidding limits which limit DN values to under 1,500,000. DN is a speed factor used to gauge the suitability of rolling element bearings to high speed applications; it is the bore diameter D in millimeters, multiplied by the shaft rotational speed N in revolutions per minute. The DN numbers are thus surface speed values and are affected by bearing design characteristics, which include surface finishes, retainer strength, friction properties, and internal clearances. Each "standard" bearing could therefore be assigned a DN value which establishes its upper speed limit. Table 5-5 lists general DN limits for ball and roller bearings.

Table 5-5

SPEED LIMITS FOR BALL AND ROLLER BEARINGS[a]

Lubrication	DN Limit (mm × rpm)
OIL	
Conventional bearing designs	300,000 to 350,000
Special finishes and separators	1,000,000 to 1,500,000
GREASE	
Conventional bearing designs	250,000 to 300,000
Silicone grease	150,000 to 200,000
Special finishes and separators	
High-speed greases	500,000 to 600,000

(a) See Ref. 5-1.

Another empirical formula used to define bearing speed limits is the TAC method developed by the engineers at the Marlin-Rockwell Division (MRC) of TRW, Inc. The formula is as follows:

$$\text{TAC factor} = \frac{D' N^3 d^3}{\cos^3 B}$$

where

D' = bearing pitch, diameter (mm)
N = bearing speed (rps)
d = ball diameter (in.)
B = initial contact angle (deg)

This formula was derived from analysis of thousands of high-speed bearing applications in aircraft engines and machine tools. It makes up for much of the shortcomings in the DN factor system because it uses the bearing pitch diameter instead of the bore diameter and, further, includes the ball size and contact angle as influencing factors. A TAC factor as high as 31×10^8 is sometimes suggested for use in the absence of empirical data. Figure 5-2 charts speeds obtained by using this limit. This figure is based on the calculations contained in Appendix H. The figure also shows lower speeds based on a lower TAC value chosen from an "experience chart" (Fig. 5-3). This experience chart indicates that 7×10^8 is a more realistic value for the TAC value. The speed obtained using 7×10^8 is the shorter of each pair of bars in Fig. 5-3. Each of these speed selection parameters has shortcomings, but each may be used for safely establishing an approximate size.

The selection of a rolling bearing to support the flywheel shaft was based on detailed evaluation of the characteristics summarized in Table 5-2, the speed limits, and the following additional considerations:

- The rolling bearing is superior to the sliding bearings in producing minimum drag at the flywheel operating speed.
- Although the transmission will have a pressure oil system to lubricate vital parts, the complexity of the system to supply the large quantities of oil necessary for a sliding bearing will add cost and weight. Sliding bearings are poorest at start-up, especially at low temperatures.
- Rolling element bearings will tolerate a wider range of operating temperature and are especially reliable for low-temperature start-up since they have low breakaway torques.

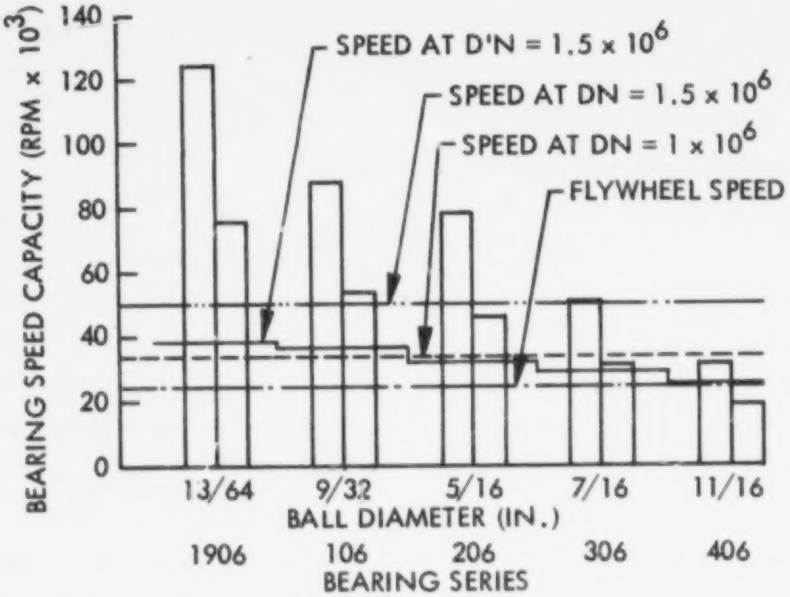


Fig. 5-2 Relationship of Bearing Speed Capacity to Ball Diameter

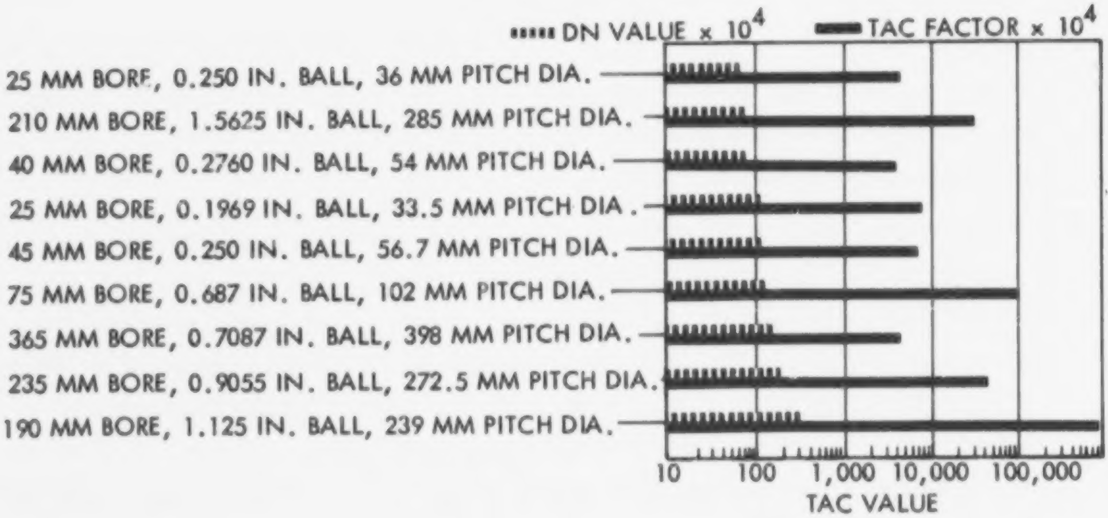


Fig. 5-3 TAC Experience Chart

Application of the AFBMA* life analysis methods (Appendix H) resulted in the size selection of a medium series Conrad type ball bearing with a nominal L_{10} life of 3,154 hr. The basic bearing dimensions are as follows:

• Bore	30 mm
• Width	16 mm
• Outer diameter	62 mm
• Ball Bearing	5/16 in.

The prevailing higher-than-normal speeds necessitate the use of bearings manufactured to better than ABEC-1** tolerances (See Ref. 5-2). However, instead of selecting a standard super-precision bearing that would be costly, the manufacturing tolerances are tailored to the application by specifying tight concentricity and roundness limits only as necessary. In this way, bore, OD, and width tolerances will remain open, but roundness of the diametral dimensions, race-to-face squareness, and conforming raceway concentricities will provide running characteristics comparable to ABEC-5 bearings

SEALS

The rotary seal around the flywheel support shaft must minimize oil and air leakage into the flywheel vacuum chamber to maximize flywheel efficiency and to permit the use of reasonably small vacuum pump. The leakage rate is the primary factor in determining the pump size.

The importance of low leakage is illustrated in Fig. 5-4 which shows that only a 0.4 cfm pump is required for pumping down the small volume and the added capacity requirement is proportional to air leakage. In other words, the smaller the leak, the smaller the pump.

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*Anti-Friction Bearing Manufacturers' Association, Inc.

**Annular Bearing Engineers' Committee

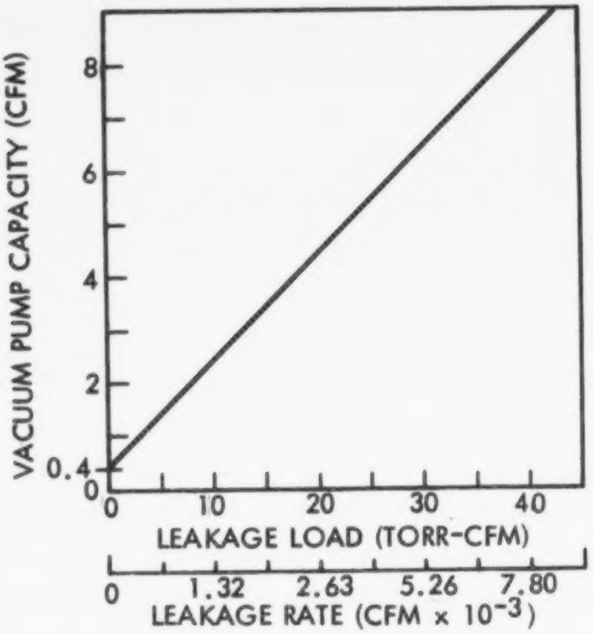

Fig. 5-4 Pump Size Vs. Leakage Rate

Specific seal design requirements are as follows:

- Size Requirement.
  - Shaft size = 1.44 in. diam.
  - Axial length = 0.75 in. max.
  - Other diam. = as required
- Operating Requirements. Following are the governing operating conditions:
  - Speed. Shaft rotation speed spectrum per the following:

% Time	Speed (rpm)
5	24,000
5	22,000
15	20,000
35	18,000
20	14,000
10	12,000
10	8,000

- Temperatures.
  - Ambient temperatures -25° F to 115° F
  - Operating temperature 220° F (nom)
- Lubrication. (Not shown on drawings.)
  - Splash from oil jets lubricating adjacent bearings
  - Type of oils: SAE 10-30 or automatic transmission fluid
- Sealing Requirements.
  - Pressure difference across seal = 15 psi
  - Oil leakage rate
    - (1) 10 drops/day (maximum allowable)
    - (2) 5 drops/day (desired maximum)
  - Allowable air leakage rate
    - (1) 0.1 cu ft/min (maximum allowable)
    - (2) 0.01 cu ft/min (desired maximum)
- Dimensional.
  - Shaft end play: none (preloaded bearings)
  - Shaft/housing runout: estimated at 0.002 in. TIR (maximum)
  - Axial tolerance stackup: design for shimming within 0.001 in.
- Cooling Provision. None, other than recirculating oil used for bearing lubrication and cooling
- Drag Torque.
  - Static 0.24 lb-in. (max.) per seal
  - Dynamic torque per seal
    - (1) 0.24 lb-in. (max.) at 24,000 rpm (required)
    - (2) 0.12 lb-in. (max.) at 24,000 rpm (desired)
- Life Requirements. 3,500 hr of operation per schedule shown above.

Available seal designs for rotating shafts fall into two major categories – contacting and noncontacting seals. The noncontacting types are represented by the labyrinth seal usually associated with fixed turbine installations. A brief evaluation of the labryrinth seal revealed leakage to be excessive (see Appendix I) with respect to sealing the flywheel housing vacuum chamber, and only contacting seals were therefore considered.

In the contacting category, a second major breakdown divides the contact type seals into two types. The first is the lip seal with its sealing action provided by an interference fit between a smooth rotating shaft surface and a flexible sealing element. The sealing element is usually made of leather or synthetic elastomers and the interference fit is usually augmented by spring pressure provided by a garter type or finger type spring. The second contact type seal is the "face seal" which creates dynamic sealing in a plane vertical to the shaft axis. This type of seal has two parts – the seal cartridge, consisting of the housing, end face (nose) element, and spring assembly; and the rubbing ring, which is the mating element that provides a smooth flat sealing surface. For high speeds, the end face is normally made of carbon and treated to reduce friction, and the mating ring is made of close-grained cast iron or steel. Table 5-6 is a brief summary of characteristics of the two groups of contact seals.

Table 5-6
SEAL CHARACTERISTICS

Parameter	Lip Seals	Face Seals
Nominal Speed Rating	0 to 3,000 fpm	0 to 50,000 fpm
Life	Good	Good to excellent
Dynamic Friction	Good to poor	Good to excellent
Cost	Low	High
Ease of Replacement	Good	Normal
Misalignment Tolerances	Excellent for axial runout; good for radial runout	Excellent for radial runout; good for axial runout
Fluid Leakage	12 to 48 drops/day	2 to 3 drops/day
Gas Leakage		0.005 cfm

In addition to the high-speed performance required of the seal, low air-leakage rates and low horsepower absorption are necessary for maximum system efficiency. Discussions with seal manufacturers revealed that these parameters were considered relatively unimportant for most applications, and that users rarely if ever specified low drag or low gas-leakage rates in specifications.

Preliminary figures for power loss were obtained using the coefficient of friction of carbon bearings and applying it to the following formula:

$$hp = \frac{P \cdot \mu \cdot r \cdot N}{63,025}$$

where

P = axial force (lb)
μ = coefficient of friction
r = mean radius of seal nose (in.)
N = shaft speed (rpm)

Values thus obtained (Appendix I) were used for all the preliminary flywheel seal losses.

Information on face seal air-leakage rates was also scarce. An estimate of 0.1 cfm was made after discussions with several seal manufacturers. The paucity of information prompted a seal test program aimed at determining true rates of seal leakage and horsepower loss. The test results are presented in Appendix J and summarized in the following paragraphs.

The seal used for the test program was a Cartriseal face seal (Part No. 1-1875-2). The basic design characteristics for this seal are as follows:

• Outer diameter (in.)	2.505 ± 0.001
• Inner diameter (in.)	1.795
• Overall length (in.)	0.739−0.734 installed

• Pressure side	Outer diameter
• Nose load	15 lb nom
• Nose material	Carbon
• Rubbing ring material	Steel
• Rubbing ring flatness	3 lightband He
• Spring force	5 lb

Anticipated conditions were simulated by mounting the rubbing ring on a high-speed spindle shaft and the cartridge into a cylindrical housing (as shown in Appendix J, Fig. J-2) which was in turn mounted to a torque sensor unit. Flywheel housing volume was simulated with a tank connected by laboratory vacuum hose to the cylindrical cartridge housing. Test results showed the preliminary estimates of horsepower loss to be too high. Leakage rates were also lower than estimated, resulting in the possible ultimate use of a smaller vacuum pump. Tabulations of calculated leakage rates based on test data, as a function of speed and nose loading, are given in Appendix J.

From the tests, it was concluded that a maximum leak rate of 0.010 cfm is possible with a standard face seal and that the drag loss will be approximately 0.5 hp per pair of seals at 24,000 rpm.

These values are used in calculating seal losses and determining vacuum pump size and power for the final baseline flywheel configuration.

VACUUM PUMP

A vacuum pump is required to maintain a low level of air pressure in the flywheel housing to minimize flywheel power losses caused by air friction. This windage loss is plotted for the baseline flywheel, as shown in Fig. 5-5, which illustrates that a vacuum level of 0.01 atm (7.6 mm Hg) or better will keep windage losses below 0.5 hp.

A review of vacuum technology and available equipment shows that much has been done in the low and high vacuum areas. Unfortunately, technology for the medium-vacuum,

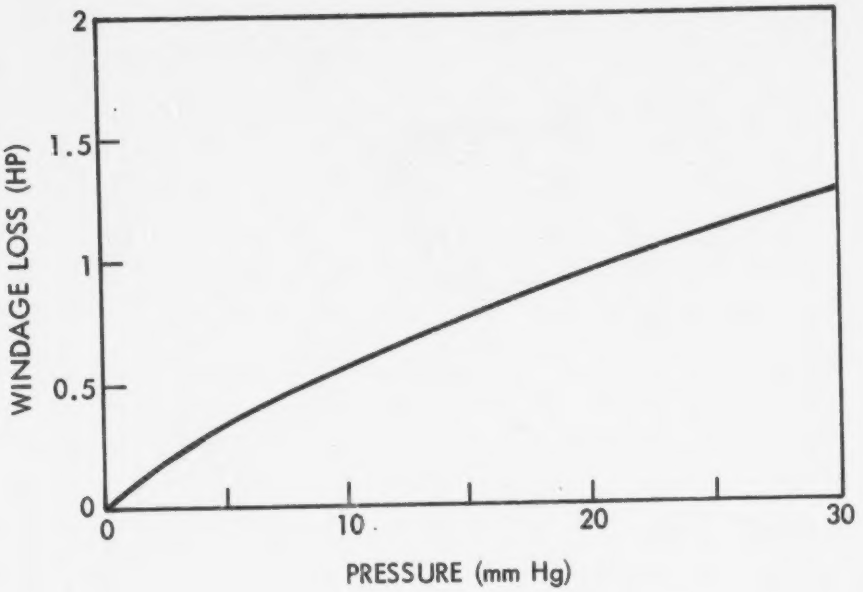

Fig. 5-5 Windage Loss Vs. Pressure for an 0.5 kW-hr Car Flywheel

low-flow requirement of the flywheel falls in a limited use zone where few suitable pumps are available.

The vacuum levels can be classed as follows:

• Low vacuum	760 to 25 mm Hg
• Medium vacuum	25 to 10^{-3} mm Hg
• High to ultrahigh vacuum	10^{-3} mm Hg and up

Commonly used vacuum systems fall into the low vacuum levels associated with the needs of the processing or materiel-handling industries or into the high to ultrahigh vacuum utilized in the laboratories to simulate space conditions.

The vacuum level required for the flywheel chamber ranges from 30 mm Hg down to under 5 mm Hg, depending on flywheel and flywheel housing design. Industrial pumps

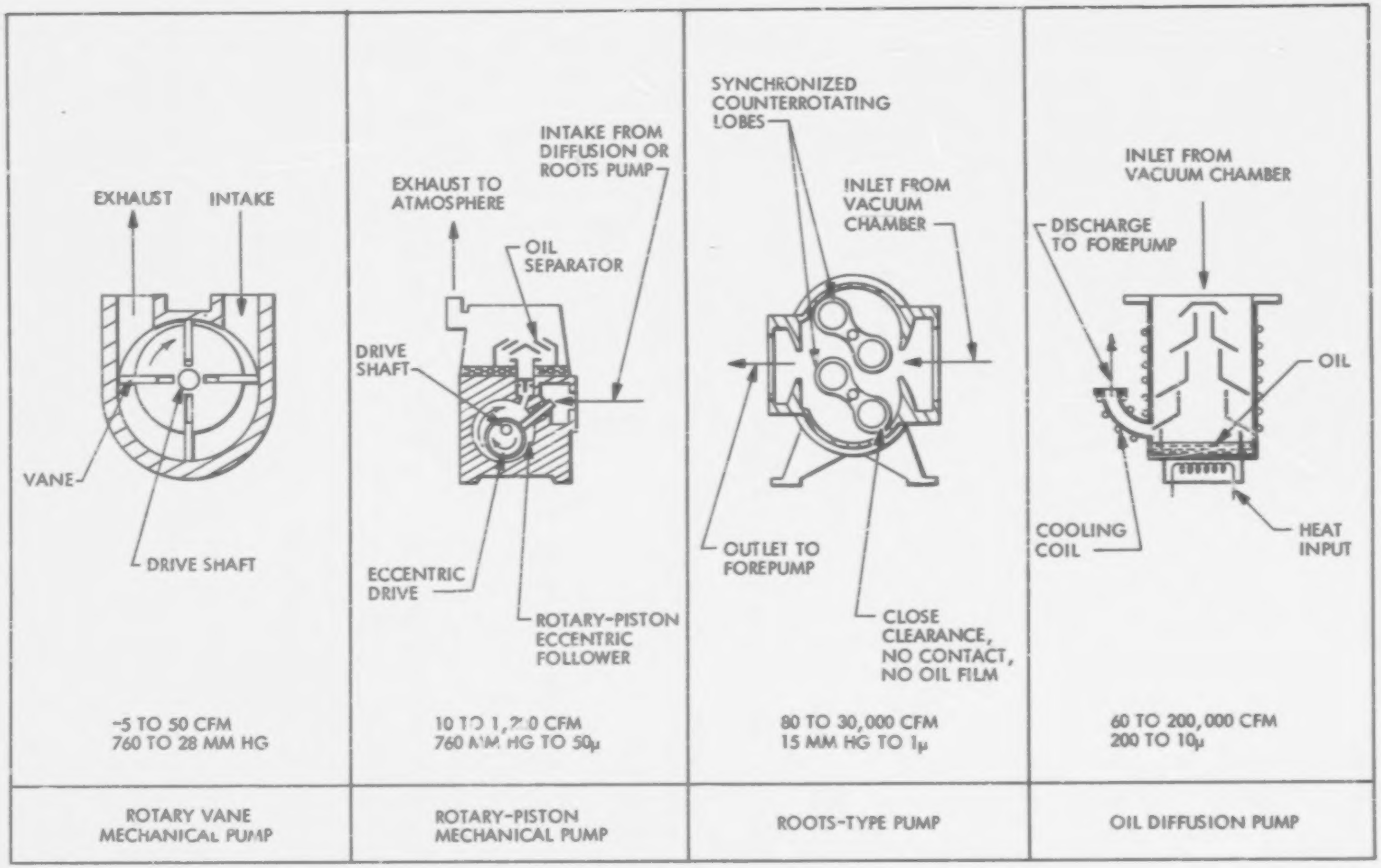
EXHAUST
INTAKE
VANE
DRIVE SHAFT
~5 TO 50 CFM
760 TO 28 MM HG
ROTARY VANE MECHANICAL PUMP
EXHAUST TO ATMOSPHERE
INTAKE FROM DIFFUSION OR ROOTS PUMP
OIL SEPARATOR
DRIVE SHAFT
ECCENTRIC DRIVE
ROTARY-PISTON ECCENTRIC FOLLOWER
10 TO 1,200 CFM
760 MM HG TO 50μ
ROTARY-PISTON MECHANICAL PUMP
SYNCHRONIZED COUNTERROTATING LOBES
INLET FROM VACUUM CHAMBER
OUTLET TO FOREPUMP
CLOSE CLEARANCE, NO CONTACT, NO OIL FILM
80 TO 30,000 CFM
15 MM HG TO 1μ
ROOTS-TYPE PUMP
INLET FROM VACUUM CHAMBER
DISCHARGE TO FOREPUMP
OIL
COOLING COIL
HEAT INPUT
60 TO 200,000 CFM
200 TO 10μ
OIL DIFFUSION PUMP

Fig. 5-6 Types of Vacuum Pumps

are usually of the vane or piston types and the vacuum pressure level is limited to about 28 to 29 in. of Hg, with shaft speeds seldom exceeding 3,500 rpm. Figure 5-6 shows the basic types of vacuum pumps that are commercially available. Pumps are arranged from left-to-right in ascending order with respect to vacuum level capability.

The flywheel/transmission environment requires a simple, low-cost, maintenance-free pump. Of those depicted in Fig. 5-6, the rotary vane comes closest to these requirements. However, its lowest vacuum levels only approach the upper limits of air pressure that can be tolerated within the flywheel housing. The others have the necessary vacuum capability but are too complex, expensive, and heavy for effective use on the transmission.

The final selection is the gerotor type mechanical pump shown in Fig. 5-7. It is a lightweight, simple, mechanically-driven pump used successfully for many years as a fluid pump for transmissions and hydraulic systems.

The operation of the pump is illustrated in Fig. 5-8. The pumping mechanism consists of two elements, an inner rotor and outer rotor. The inner element always has one less tooth than the outer.

The volume of the "missing tooth" multiplied by the number of driver teeth determines the volume of fluid pumped at each revolution (cubic displacement per revolution). The number of teeth may vary, depending on such design considerations as volume to be pumped, speed, and available pump envelope, but the inner element always has one less tooth than the outer.

As the toothed elements, mounted on fixed centers but eccentric to each other, turn, the chamber between the teeth of the inner and outer elements gradually increases in size through approximately 180 deg of each revolution until it reaches its maximum size – equivalent to the full volume of the "missing tooth." During this initial half of the cycle, the gradually enlarging chamber is exposed to the suction port creating a partial vacuum into which the liquid flows. During the subsequent 180 deg of the

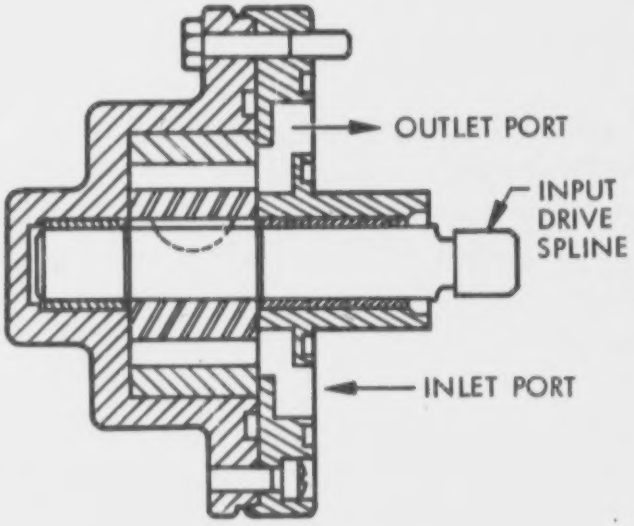
OUTLET PORT
INPUT DRIVE SPLINE
INLET PORT

Fig. 5-7 Gerotor Type Mechanical Pump – Cross Section

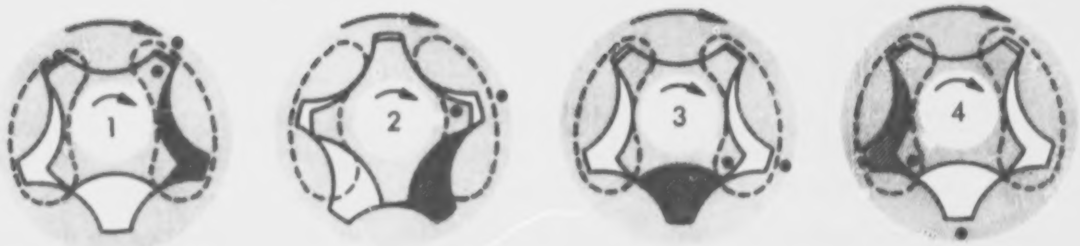

Fig. 5-8 Operating Cycle of Gerotor Pump

revolution, the chamber gradually decreases in size as the teeth mesh and the fluid is forced out the discharge port.

The pump configuration, consisting of an internal gear and mating rotor, provides inherent advantages suited to the higher speeds associated with the flywheel transmission. Both elements revolve in the same direction and the relative speed between them is proportional to the tooth ratio; thus, high shaft speeds result in low relative pump element speeds. Rotor speeds of 7,000 to 8,000 rpm on medium-sized pumps (2-in. diam.) are common, and speeds approaching 60,000 rpm have been run successfully on smaller units.

The basic sizing formula for the vacuum pump is

$$C_p = \frac{2.3}{\Delta T} (V) \log \left(\frac{P_1}{P_2} \right) + \frac{Q_o + Q_2}{P_2}$$

where

C_p = pump load capacity (cfm)
ΔT = pumpdown time (min)
V = free volume in flywheel housing (ft^3)
P_1 = initial pressure (mm Hg, abs)
P_2 = final or working vacuum pressure (mm Hg, abs)
Q_o = outgassing load (Torr-cfm)
Q_2 = leakage load (Torr-cfm)

The baseline pump size using the formula is 3.54 cfm. Detailed pump claculations are given in Appendix K.

The first term of the formula is governed primarily by the volume and pumpdown time. It represents the pump size required if outgassing and leakage are assumed to be zero. The second part represents the pump size requirement due to outgassing and leakage. The small outgassing surface areas involved and the type of materials used for the flywheel and housing contribute to a negligible outgassing load, conservatively estimated as 0.5 Torr-cfm. The leakage rate Q_L is the most important factor in sizing a pump for a flywheel housing. A plot of pump size versus leakage rate is shown in Fig. 5-4.

Since the primary use of a gerotor type pump is for positive pressure, there was little information available for its use as a vacuum pump. Discussions with engineering personnel representing the W. H. Nichols Company (Waltham, Mass.) provided the necessary impetus for further investigation. Tests were conducted on a two-element pump assembly at the Nichols Company and at the LMSC Ground Vehicle Test Facilities in Sunnyvale, California (Ref. 5-3). The important parameters under test were as follows:

- Maximum vacuum level attained
- Pumpdown time
- Driving power requirements

The tests simulated the conditions that a vacuum pump would encounter in a flywheel transmission. The conclusion drawn from the test results is that the pump provides the performance requirements necessary to make it acceptable for use as the vacuum pump in the flywheel transmission. Test results are summarized in the following paragraphs.

The pump sustains low air-pressure levels consistently under 5.0 mm Hg, and the pumpdown time to 10 mm Hg never exceeded 25 sec, even at the lowest test run speed of 5,200 rpm. Figure 5-9 shows a typical pumpdown time plot from the test recorder.

It should be noted that the pump used was not designed specifically for the application – it was designed for use as a scavenger pump in a gas turbine. The only adaptation made for pump operation was to provide approximately a 10-in. head of oil in a standpipe on the discharge port. This ensured continuous lubrication for the rotors and provided "oil sealing" between parts.

A special pump designed for the application would incorporate anti-friction bearings on the shaft and positive lubrication of the rotor. In normal use of the gerotor-type

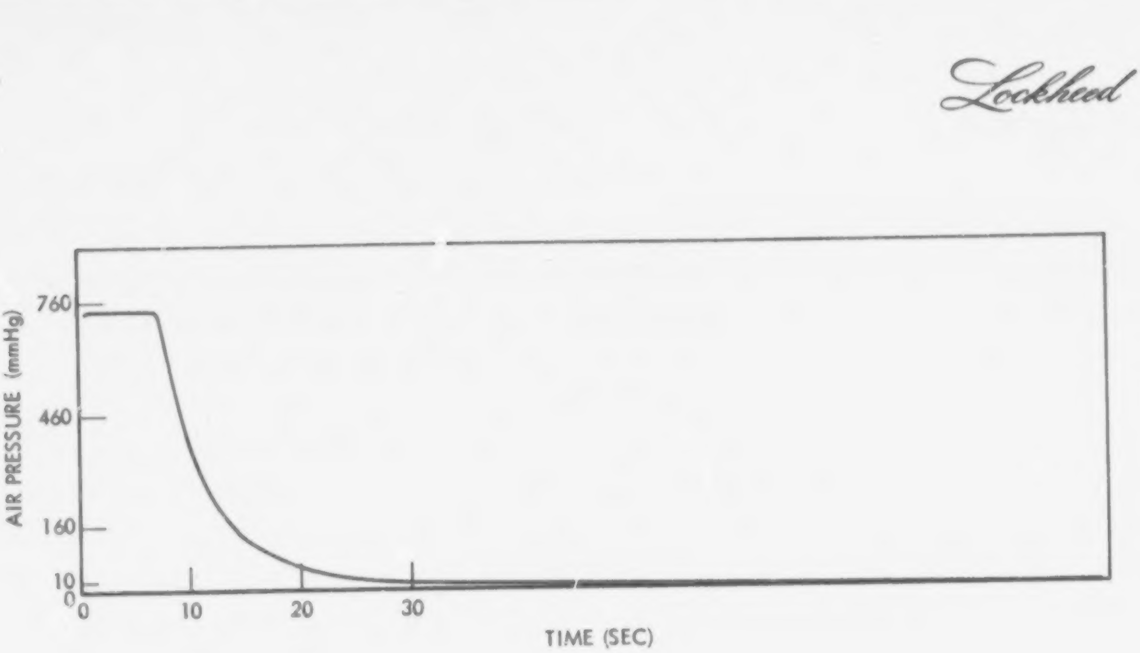

Fig. 5-9 Recorder Data – Pumpdown-Rate Curve

pump (in a pressure or scavenging application), there is no need for these special features because the fluid flow through the pump is sufficient to lubricate and to disperse heat. However, as a vacuum pump, it does not have the oil flow necessary for lubrication and cooling. A second set of pump elements, adjacent to the vacuum elements and driven by the same shaft, could provide the necessary cooling for the vacuum pumping elements. This second set of elements would be used as a low-pressure lubrication pump or as a scavenge pump for the flywheel system and/or transmission.

PRELIMINARY FLYWHEEL DESIGNS

In order to assist the transmission contractors in the task of integrating the flywheel system into the overall transmission, preliminary designs were made of several configurations.

The design of high energy density flywheels is covered in Ref. 1-1. The incorporation of burst containment structures dictated a reduction in flywheel diameter in order to comply with automotive space requirements. These space constraints vary with flywheel location and orientation as shown in Figs. 5-10, 5-11, and 5-12.

Preliminary Flywheel Design 1, shown in Fig. 5-10, was configured for a horizontal longitudinal axis at the back of a rear wheel drive transaxle. The relatively small diameter is dictated by the road clearance angle of departure.

Figure 5-11 shows Preliminary Flywheel Design 2 which was configured for mounting between the engine and the transmission with a through-hole for the engine driveshaft.

Preliminary Flywheel Design 3, shown in Fig. 5-12, is configured for mounting over a rear transaxle. This flywheel design is the same as that of the flywheels built and tested by LMSC under a previous EPA contract (Ref. 1-1).

Weight, power loss, and cost estimates for Preliminary Flywheel Designs 1, 2, and 3 are given in Tables 5-7, 5-8, and 5-9, respectively. Calculations for flywheel windage losses and pumping requirements are contained in Appendix G.

BASELINE DESIGN

After completion of the studies and tests on flywheel ancillaries, a final baseline design was defined. Figure 5-13 shows a cross-sectional layout of the baseline flywheel installation. The spin axis is horizontal and the power takeoff spline is on one end. The flywheel is straddle-mounted between a pair of single-row, deep-groove, Conrad-type ball bearings. The bearing mounting arrangement fixes the inner and outer races of the bearing located to the right. The left bearing inner race is fixed to the shaft and the outer race is spring-loaded to effect a face-to-face duplex mounting arrangement. This arrangement fixes the flywheel shaft while maintaining sufficient preload on the

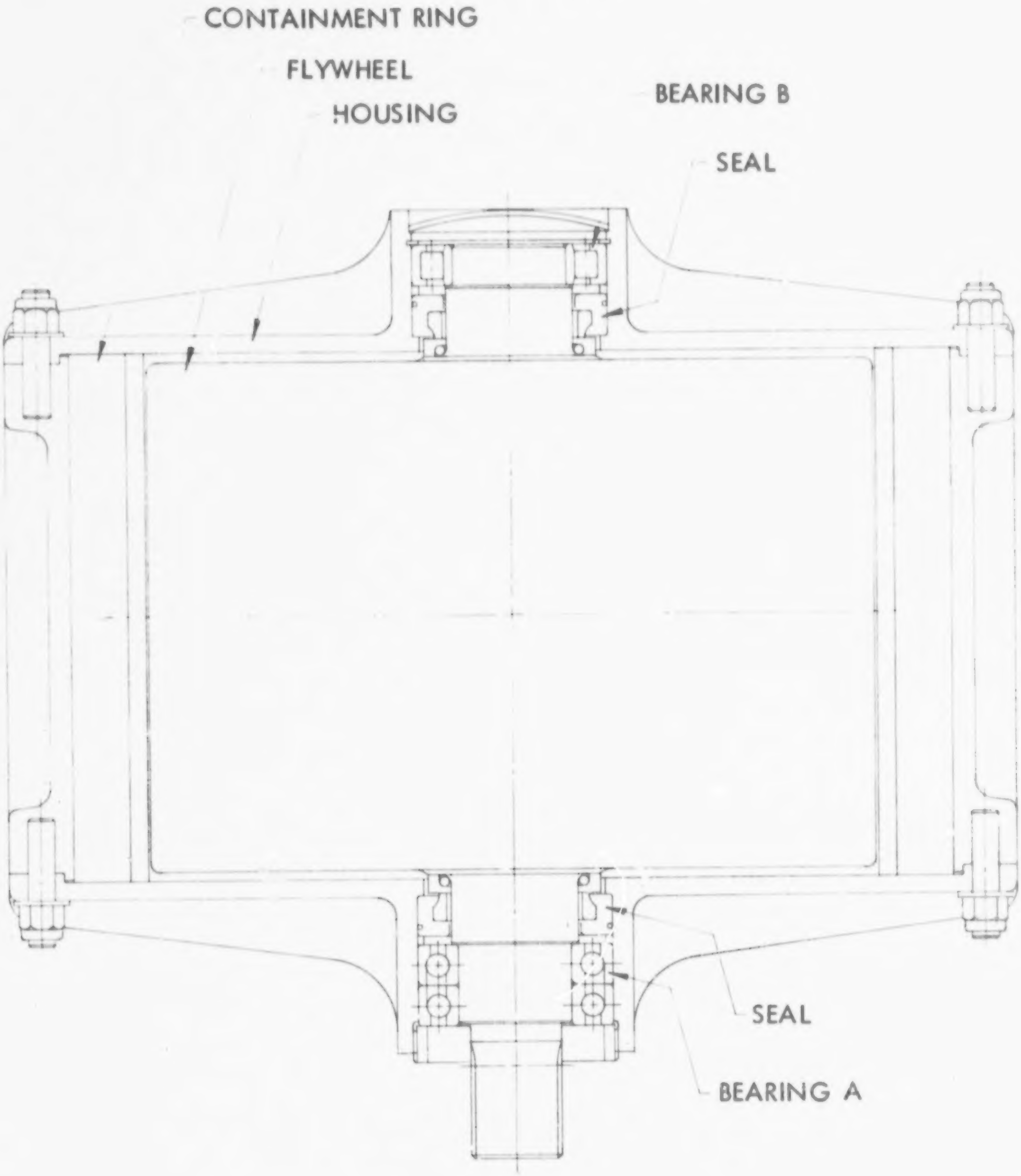
CONTAINMENT RING
FLYWHEEL
HOUSING
BEARING B
SEAL
SEAL
BEARING A

Fig. 5-10 Preliminary Flywheel Design 1

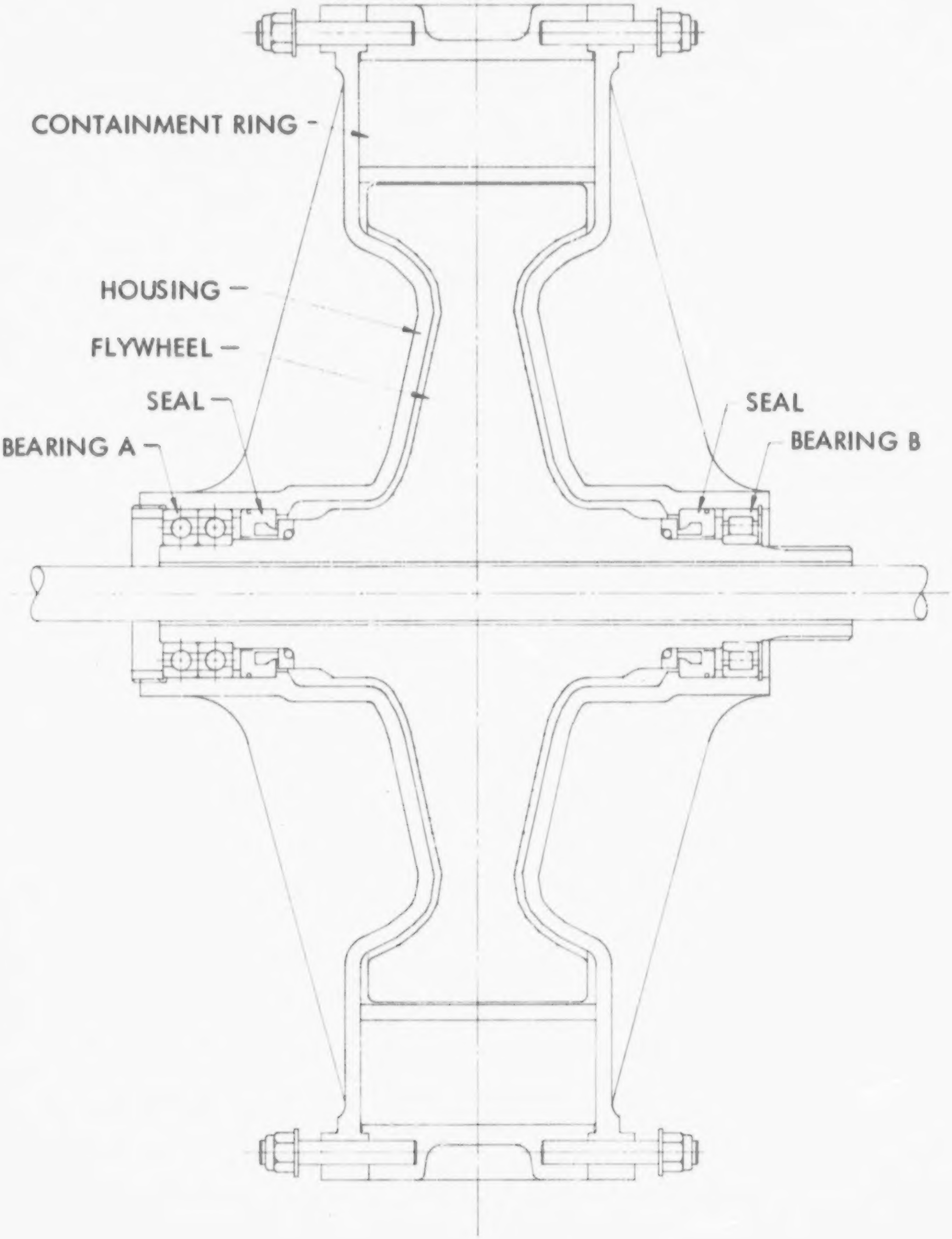
CONTAINMENT RING
HOUSING
FLYWHEEL
SEAL
BEARING A
SEAL
BEARING B

Fig. 5-11 Preliminary Flywheel Design 2

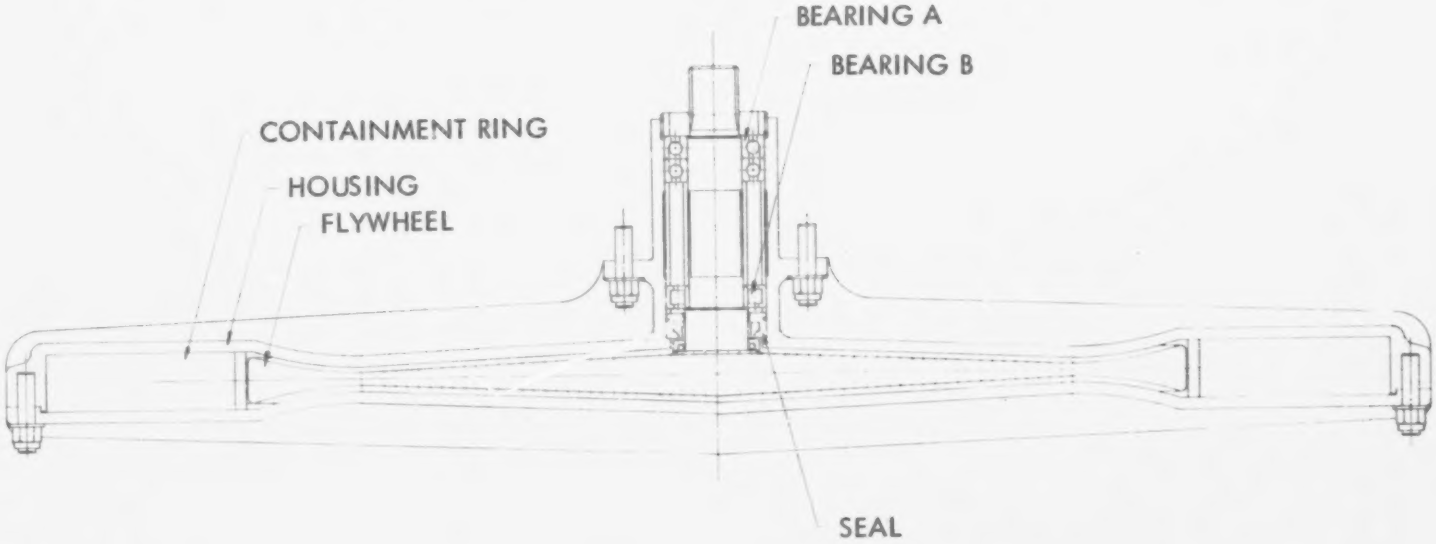
BEARING A
BEARING B
CONTAINMENT RING
HOUSING
FLYWHEEL
SEAL

Fig. 5-12 Preliminary Flywheel Design 3 (Family Car)

Table 5-7

FLYWHEEL ASSEMBLY DATA
PRELIMINARY FLYWHEEL DESIGN 1
(Based on Available Information Nov. 2, 1971)

I. CONFIGURATION

Flywheel 10.00 dia. per LMSC Dwg. No. SK 20-2101

II. WEIGHT BREAKDOWN

Flywheel	161.0 lb
Containment ring	30.15
Bearing set "A"	0.90
Bearing "B"	0.45
Seal (2)	0.24
Housing	26.9
Housing covers	45.4
Bearing Ret. Nut	0.21
Vac pump element	0.46
Misc	2.82
Total	268.53 lb

III. POWER LOSS

	Speed RPM				
	28000	24000	18000	12000	8000
Windage	1.722	1.118	0.500	0.161	0.052
Bearing	0.301	0.190	0.080	0.024	0.007
Seal (2)	0.224	0.192	0.144	0.096	0.064
Lube pump	0.016	0.016	0.016	0.016	0.016
Vac Pump	0.09	0.09	0.09	0.09	0.09
Total Loss (hp)	2.353	1.606	0.830	0.387	0.229

Conditions: (1) 30 mm Hg press in housing
(2) Face type rotary seal
(3) Seal leakage rate 0.1 cfm
(4) Vac pump capacity 3 cfm

Table 5-7 (Cont.)

IV. ESTIMATED UNIT COST

Flywheel 10.00" diameter per LMSC drawing no. SK-20-2101

	Production Quantities at:	
Description	100,000/year	1,000,000/year
Flywheel	$ 43.51	$ 42.30
Containment ring	11.44	10.51
Bearing Set "A"	8.00	7.14
Bearing "B"	4.00	3.57
Seal (2)	7.70	6.86
Housing	10.90	10.41
Housing covers	19.00	18.04
Bearing Retainment Nut	.91	.82
Vacuum Pump Element	4.75	4.23
Studs, Nuts, Washers, etc.	1.91	1.84
Assembly	1.98	1.50
Total Unit Cost	$114.10	$107.22
Initial Cost of Required Machinery & Equipment	$1,956,000.00	$10,580,000.00

Note: Above unit cost does not include profit.

Table 5-8

FLYWHEEL ASSEMBLY DATA
PRELIMINARY FLYWHEEL DESIGN 2
(Based on Available Information Nov. 2, 1971)

I. CONFIGURATION

Flywheel 13.06 dia per LMSC Dwg. No. SK 20-2102

II. WEIGHT BREAKDOWN

Flywheel	86.16 lb
Containment Ring	33.45
Bearing set "A"	0.90
Bearing "B"	0.45
Seal (2)	0.24
Housing ring	21.67
Housing cover (2)	40.50
Bearing nut	0.21
Vac pump element	0.46
Misc	2.82
	186.86 lb

III. POWER LOSS

	Speed RPM				
	28000	24000	18000	12000	8000
Windage	3.112	2.021	0.903	0.290	0.093
Bearing	0.162	0.102	0.043	0.013	0.004
Seal (2)	0.224	0.192	0.144	0.096	0.064
Lube pump	0.016	0.016	0.016	0.016	0.016
Vac pump	0.090	0.090	0.090	0.090	0.090
Total Loss (hp)	3.604	2.421	1.196	0.505	0.267

Conditions:
(1) 30 mm Hg pressure in housing.
(2) Face type rotary seal.
(3) Seal leakage rate 0.1 cfm
(4) Vac pump capacity 3 cfm

Table 5-8 (Cont.)

IV. ESTIMATED UNIT COST

Flywheel 13.06" diameter per LMSC Drawing No. SK-20-2102

Description	Production Quantities at: 100,000/year	1,000,000/year
Flywheel	$25.60	$24.37
Containment Ring	13.00	12.06
Bearing Set A	8.00	7.14
Bearing B	4.00	3.57
Seal (2)	7.70	6.86
Housing Ring	9.15	8.68
Housing Cover	17.40	16.43
Vacuum Pump Element	4.75	4.23
Bearing Retainment Nut	.91	.82
Studs, Nuts, Washers, etc.	1.51	1.46
Assembly	1.98	1.50
Total Unit Cost	$94.00	$87.12
Initial cost of required Machinery & Equipment	$1,956,000.00	$10,580,000.00

Note: Above unit cost does not include profit

Table 5-9

FLYWHEEL ASSEMBLY DATA
PRELIMINARY FLYWHEEL DESIGN 3

(Based on Information Available on Nov. 2, 1971)

I. CONFIGURATION

Flywheel, 20.44 diameter per LMSC Drawing No. SK 20-2103

II. WEIGHT BREAKDOWN

Flywheel	44.11 lb
Containment ring	33.45
Bearing set "A"	0.56
Bearing "B"	0.28
Seal (1)	0.12
Housing	74.54
Housing cover	71.90
Spacers	0.83
Vac pump element	1.84
Bearing ret. nut	.21
Misc	2.00
Total	229.84 lb

III. POWER LOSSES

	Speed RPM				
	28000	24000	18000	12000	8000
Windage	3.201	2.076	0.922	0.296	0.095
Bearing	0.112	0.071	0.030	0.090	0.003
Seal (1)	0.113	0.096	0.072	0.048	0.032
Lube pump	0.016	0.016	0.016	0.016	0.016
Vac pump	0.247	0.247	0.247	0.247	0.247
Total Loss (hp)	3.689	2.506	1.287	0.697	0.393

Conditions:
(1) 5 mm Hg press in housing
(2) Face type rotary seal
(3) Seal leakage rate 0.1 cfm
(4) Vac pump capacity 13.0 cfm

Table 5-9 (Cont.)

IV. ESTIMATED UNIT COST

Flywheel 20.44" diameter per LMSC drawing no. SK-20-2103

Description	Production Quantities at: 100,000/year	1,000,000/year
Flywheel	$ 15.50	$ 14.29
Containment ring	14.39	13.45
Bearing set "A"	8.00	7.14
Bearing "B"	4.00	3.57
Seal (1)	3.85	3.43
Housing	26.61	26.13
Housing cover	27.74	26.79
Spacers	.10	.10
Bearing retainment nut	.91	.82
Vacuum pump element	3.00	2.68
Studs, nuts, washers, etc.	1.71	1.63
Assembly	1.98	1.50
Total Unit Cost	$107.79	$101.53
Initial cost of required Machinery & Equipment	$1,956,000.00	$10,580,000.00

Note: Above unit cost does not include profit.

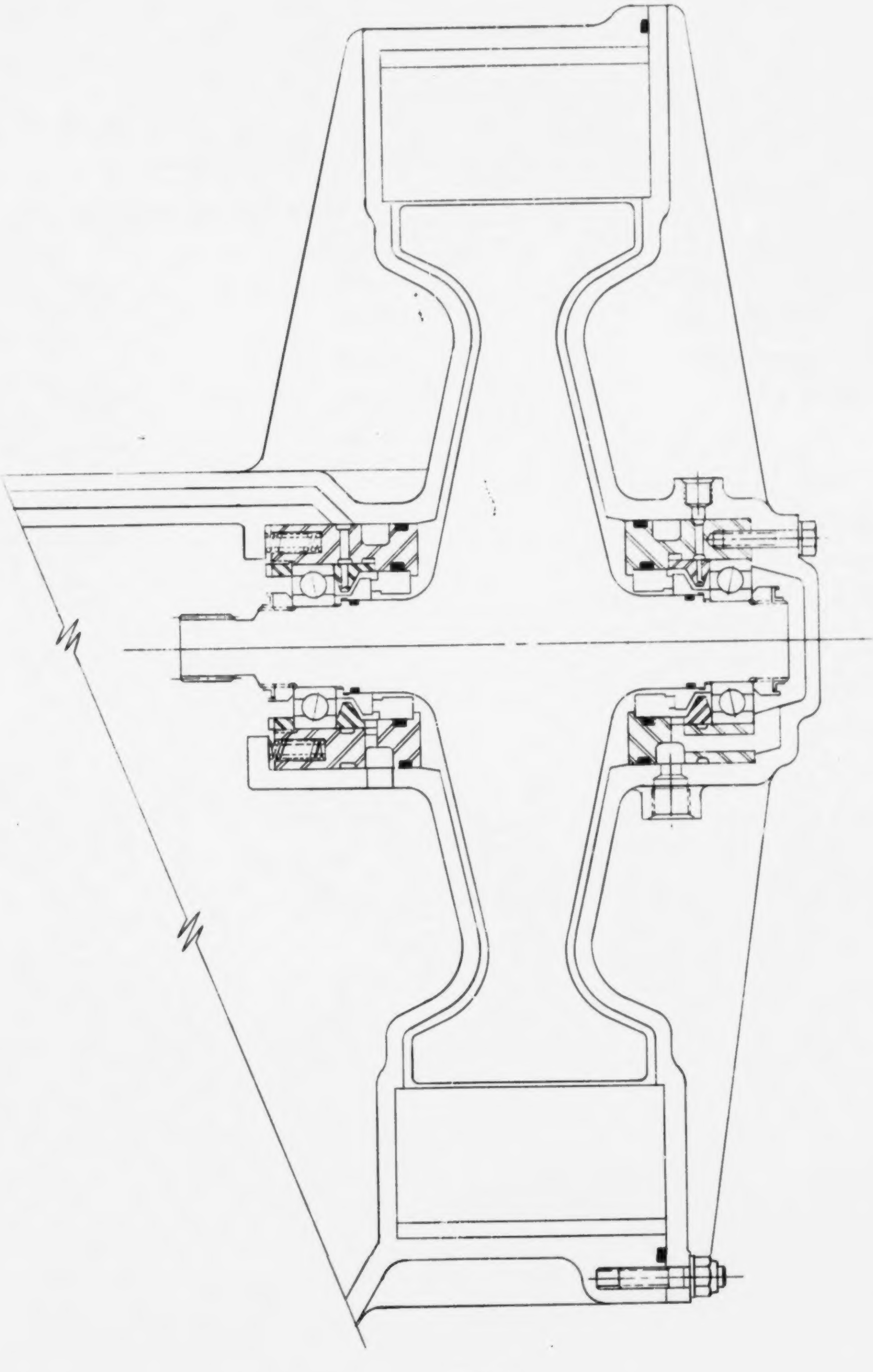

Fig. 5-13 Baseline Flywheel

bearing so that the balls are in contact with the raceways eliminating the possibility of ball skidding. Bearing tolerances are nominally ABEC 1 except for specified concentricity and roundness limits. Outer diameter and width tolerances are loose but the roundness, face-to-race squareness, and conforming raceway concentricity will provide the necessary high-speed running characteristics comparable to precision ABEC 5 bearings. The ball retainer is a one-piece, outer-race-riding type particularly suited for high speeds. Nominal L_{10} life for each bearing is 3, 157 hr based on the use of 52100 vacuum degassed steels.

Vacuum sealing of the flywheel chamber at the shaft penetrations is accomplished by the two carbon face seals.

Oil for lubricating and cooling the bearings and seals is taken from the transmission lubrication system, and the vacuum pump (not shown on layout) is designed to be pad-mounted and driven by the transmission or engine accessory drive system. One oil jet per bearing is normally sufficient but two per bearing is used to provide redundancy as insurance against oil starvation in case of a clogged oil jet. The oil jet orifice is 0.030 in. in diameter as a result of experience which establishes this as the smallest practical jet diameter normally able to pass foreign materials, e.g., lint, metal particles, and products of wear commonly found in transmission oil systems.

The violent oil misting action created when the oil jet impinges the rotating bearing race and balls supplies the seal lubrication. A very important feature of the flywheel installation is the large drain passages provided to ensure thorough draining and scavenging of the "used oil" from the space surrounding the bearings and seals. This will ensure against unwanted heat and absorption of power due to churning pockets of oil. Weight, power loss, and cost data for the baseline flywheel system design are given in Table 5-10.

Table 5-10

FLYWHEEL ASSEMBLY DATA
BASELINE DESIGN

I. CONFIGURATION

Flywheel 13.06 diameter per LMSC Drawing No. SK 20-2102

II. WEIGHT BREAKDOWN

Flywheel	86.00 lb
Containment Ring	33.45
Bearing "A"	0.50
Bearing "B"	0.50
Seal (2)	0.24
Housing Ring	21.67
Housing Cover (2)	40.50
Bearing Nut	0.21
Vac Pump Element	0.46
Miscellaneous	2.82
Total	186.86 lb

III. POWER LOSS

Item	Speed (rpm)					
	28,000	24,000	20,000	18,000	12,000	8,000
Windage	0.75	0.48	0.30	0.16	0.07	0.023
Bearing	0.074	0.052	0.036	0.024	0.014	0.001
Seals	0.520	0.46	0.400	0.34	0.28	0.22
Lubricating Pump	0.008	0.008	0.008	0.008	0.008	0.008
Vacuum Pump	0.323	0.323	0.323	0.323	0.323	0.323
Total Loss (hp)	1.675	1.323	1.067	0.855	0.695	0.575

Conditions:
(1) Vacuum pressure = 5 mm Hg
(2) Pumpdown time = 30 sec
(3) Vacuum pump capacity = 3.54 cfm
(4) Seal leakage rate = 0.010 cfm/seal

Table 5-10 (Cont.)

IV. ESTIMATED UNIT COST

Flywheel 13.06 in. diameter

Description	Production Quantities at: 100,000/year	Production Quantities at: 1,000,000/year
Flywheel	$ 25.60	$ 24.37
Containment Ring	13.00	12.06
Bearing Set	8.00	7.14
Seal (2)	7.70	6.86
Housing Ring	9.15	8.68
Housing Cover	17.40	16.43
Vacuum Pump Element	4.75	4.23
Bearing Retainment Nut	.91	.82
Studs, Nuts, Washers, etc.	1.51	1.46
Assembly	1.98	1.50
Total Unit Cost	$ 90.00	$ 83.55
Initial cost of required Machinery & Equipment	$1,956,000.00	$10,580,000.00

Note: Above unit cost does not include profit

FLYWHEEL DRIVE SIZE, WEIGHT, AND COST

FLYWHEEL DRIVE SIZE

The preferred flywheel location is at the rear axle in the form of a transaxle arrangement. Studies by the transmission contractors were in agreement with conclusions reached earlier by LMSC (Ref. 1-1) that the propulsion system volume requirements of the EPA Vehicle Design Goals (Appendix A) can be met with this approach.

FLYWHEEL DRIVE WEIGHT

By similarity, the estimated weight of the baseline flywheel assembly is approximately that of preliminary flywheel assembly design No. 2; i.e., 187 lb. The estimated weight of the heavier Sundstrand transmission configuration (8C) is 238 lb. Assuming a weight of 150 lb for a typical conventional three-speed automatic transmission, the net weight increase of incorporating a flywheel drive system is 275 lb. This weight increase is within the requirements of the EPA Vehicle Design Goal (Appendix A).

FLYWHEEL DRIVE COST

The estimated additional cost of the Sundstrand flywheel transmission over the conventional three-speed automatic transmission is $84. The estimated cost of the flywheel system is $100 plus or minus $15 depending on flywheel configuration. The net additional cost of the flywheel drive over the conventional transmission is therefore under $200. Other costs of ownership (maintenance, etc.) should be approximately the same as for a conventional transmission. On this basis, the net cost of ownership should be within the EPA Vehicle Design Goals (Appendix A).

Section 6
COMPUTER-AIDED EMISSION ANALYSIS

One of the main objectives of the Flywheel Drive Study Program was to quantify, as nearly as possible, the reduction in engine emissions that could be obtained through use of the flywheel drive. Since insufficient engine emissions data were available, the EPA assigned the task of obtaining this data to the U.S. Bureau of Mines Petroleum Research Center (PRC), (Bartlesville, Oklahoma). The EPA also stipulated that minimization of brake specific fuel consumption (bsfc) over the 1972 Federal Test Procedure dyno cycle be used as an interim criterion.

BSFC ANALYSIS

A number of computer runs over the dyno cycle were made to determine bsfc for various drive configurations. Input data on transmission efficiency were supplied by Sundstrand Aviation. A list of the runs is presented in Table 6-1. From this list, the effects of various drive system variations may be determined, as shown in Table 6-2.

The torque-speed path followed by the engine is most critical; improvements in transmission efficiency have much less effect on fuel economy. The incorporation of energy storage into idealized (lossless) transmissions shows only a slight improvement in fuel economy. If, however, the effects of engine transients on conventional drives were taken into account, the actual improvement might be much more. The air conditioning load has little effect on fuel economy, since bsfc drops with load.

The conventional transmission is shown as having a slightly better fuel economy than the flywheel transmission. This is an important result, not only from the standpoint of fuel economy per se but also because fuel economy was used as an interim criterion for emissions. There are, however, two engine phenomena which, because of a lack of data, were not taken into account, namely, transient effects and torque-speed requirements.

Table 6-1

DYNO CYCLE FUEL ECONOMY OF VARIOUS DRIVE CONFIGURATIONS

Computer Run No.	Transmission	Efficiency	Flywheel Losses (hp at 24,000 rpm)	Accessories[a]	Engine Speed	MPGA
106	8A	1	2.746	B	Curve X	8.86
107	8A	1	2.746	B	Min. BSFC	13.48
108	8A	1	0	B	Min. BSFC	14.45
108-1	8A	1	0	B w/o A/C	Min. BSFC	16.10
109	8A	Curve A	2.746	B	Curve X	7.31
110	8A	Curve A	2.746	B	Curve Y_{1059}	8.12
111	8A	Curve A	2.746	B	Curve Z_{800}	9.24
112	8A	Curve A	2.746	B w/o A/C	Curve Y	8.74
114	8A	1	2.746	B	Curve Y	10.73
113	8C	Curve B	2.746	B[a] w/o A/C	Curve Z	10.03
115	8C	1	2.746	B	Curve Z	13.74
118	HMT	Curve C	N/A	B[a] w/o A/C	Min.BSFC	10.58
119	HMT	1	N/A	B[a] w/o A/C	Min.BSFC	13.91
120	Automatic, 3-speed	Curve D	N/A	B[a] w/o A/C	Curve W	11.14
121	Automatic, 3-speed	1	N/A	B[a] w/o A/C	Curve W	11.99

(a) Per EPA Typical B Car.

Table 6-2

EFFECTS OF TRANSMISSION VARIATIONS ON DYNO CYCLE FUEL ECONOMY

Variation	From	To	Computer Run No. (a)	Difference in Average (mpg)	Percent Difference in Average (mpg)
Engine Operation	Curve X	Min. bsfc	106, 107	4.6	52.1
Transmission Efficiency	Curve A	100%	106, 109	1.5	21.2
Energy Storage	Without	With	119, 108-1	2.2	15.7
Air Conditioning	With	Without	108, 108-1	1.6	11.4
Basic Type	Conventional	Flywheel	120, 113	-1.1	10.0
Flywheel Losses	2.746 hp at 24,000 rpm	0	107, 108	1.0	7.6

(a) See Table 6-1.

In the first case, in stop-and-go driving, as in the dyno cycle, engine transient effects degrade fuel economy under conventional transmission operation. These effects can be essentially eliminated with the flywheel transmission by means of sufficient lag in throttle operation. From the standpoint of emissions, a report by Minicars, Inc. (Ref. 6-1), states that

> "The most important design configuration during this hybrid investigation is the concept of delaying the throttle in the carburetor of the ICE during transient operation."

The report concludes,

> "The hybrid power train does lower exhaust emissions. When carburetor throttle is delayed during transient accelerations and deceleration, there is a further reduction."

The second engine phenomenon not taken into account was the potential for emission reduction with the flywheel drive which results from its lower peak power requirement and its ability to function along a single line in the torque-speed plot. If the engine were designed to operate only in this restrained manner, the design compromises required for operation over a wide torque-speed area would be relieved, and it is expected that bsfc (or emissions) might be further reduced, although there is no experimental data to verify this.

Referring again to Table 6-2, the conventional transmission fuel economy is shown by the fuel consumption being only 1.1 mpg higher than that of the flywheel transmission. Considering the possible effects of the engine phenomena just discussed, it might be concluded that the dyno cycle fuel economy of the flywheel transmission could be expected to be roughly equivalent to that of the conventional transmission. Thus, from the standpoint of fuel economy per se, the flywheel transmission might be considered competitive with the conventional transmission. From the standpoint of emissions, using bsfc as an emissions criterion, it would appear that the flywheel transmission offers little or no potential for emission reduction in comparison with the conventional transmission. Analysis of the first batch of actual engine emission data from PRC, however, showed little correlation between bsfc and emissions. It was therefore evident that valid conclusions regarding the emission reduction potential of the flywheel drive will have to be based on actual engine emission data.

ANALYSIS OF PRC EMISSION DATA

Emissions analysis was performed on gasoline engine data submitted by the U. S. Bureau of Mines, Petroleum Research Center (PRC), located in Bartlesville, Oklahoma. These data were obtained by testing two Chevrolet, 350-CID engines, designated as engines A and B. The emissions were measured at various values of engine speed, percent power, air-fuel ratio, spark advance, and exhaust recirculation rate. They were measured both upstream and downstream of an Engelhard catalyst. All data were for steady-state operation of a warmed-up engine. The data, as received from PRC and computer-formatted by LMSC, are presented in Appendix M.

The analysis was made on the basis of data transmitted to LMSC by the Bureau of Mines Petroleum Research Center. (See Refs. 6-1 through 6-3.) The data thus provided may be summarized as follows:

- Ref. 6-1. Obtained through operation of engines A and B at 2,400 rpm and at 10, 25, and 50 percent of maximum power (with and without Engelhard catalyst effects), and with exhaust recirculation rates of 0, 50, and 100 percent of maximum. A range of air-fuel ratios was investigated at spark-advance values of 10, 20, and 30 deg BTC.
- Ref. 6-2. Obtained through operation of engines A and B at 1,600 rpm. and at 10, 25, 50, and 90 percent of maximum power (with and without Engelhard catalyst effects), and with exhaust recirculation rates of 0, 50, and 100 percent of maximum. A range of air-fuel ratios was investigated at spark-advance values of 10, 20, and 30 deg BTC.
- Ref. 6-3. Obtained through operation of engines A and B at 1,200 rpm and at 10, 25, 50, and 90 percent of maximum power (with and without Engelhard catalyst effects), and with exhaust recirculation rates of 0, 50, and 100 percent of maximum. A range of air-fuel ratios was investigated at spark-advance values of 10, 20, and 30 deg BTC. Included in this material were data for engine B operation at an idling speeed of 800 rpm, and knock-limited power data for engines A and B over the range of the aforementioned operating variables.

ANALYSIS OBJECTIVES

The objectives of the emissions analysis were as follows:

- Determine the rates of HC, CO, and NO_x emissions in the test engine steady-state operation
- Evaluate the ability of the engine to function at a single operating point in a hybrid-heat-engine/flywheel vehicle so that emissions are minimized
- Examine, by means of computerized sorting and plotting techniques, the sensitivity of engine emissions to the several operating variables, and determine preferred operating areas
- Identify areas for further engine emission testing which offer a potential for values of emissions lower than those already obtained.

EPA 1976 EMISSION LIMITS

The EPA-established emission limits for 1976 are as follows:

• CO	3.4 g/mi
• HC	0.41 g/mi
• NO_x	0.4 g/mi

These emission limits are based on operation over the dyno driving cycle and must be maintained at or below these levels for 50,000 miles. (See Ref. 6-5.) In order to facilitate a comparison of the PRC emissions data with these emission limits, the latter were converted from g/mi into g/hp-hr. To this end, a computer-simulated run was made of a median weight (4,300 lb) family car in accordance with the established vehicle design goals (Appendix A). The vehicle was considered as being equipped with a hydrostatic power-splitting flywheel transmission (Sundstrand version 8C). The simulation was over the dyno driving cycle. The average energy output from the engine was 0.816 hp-hr/mi. Thus the 1976 emission limits, expressed in g/mi, were divided by 0.816 hp-hr/mi, and thereby translated into g/hp-hr as shown below:

• CO	4.16 g/hp-hr
• HC	0.503 g/hp-hr
• NO_x	0.49 g/hp-hr

These conversions are only valid for steady-state engine operation and do not include any cold start effects, and therefore should be used with caution.

GENERAL EXAMINATION OF DATA

Examination of the entire mass of data reveals a number of points at which the CO and HC values are simultaneously below the converted 1976 emission levels. Only two points exist (in engine B data) at which the NO_x is equal to or below the converted 1976 levels; but at these points, the CO and HC are many times higher than their respective converted levels. Therefore, the data do not offer any point at which the converted emissions levels are met simultaneously by the three pollutants. The concentrations of CO, HC, and NO_x do not respond in similar ways to changes in spark advance or air-fuel ratio.

The data for engines A and B indicate a very significant difference between their respective emissions characteristics. In general, engine A emissions are lower than those of engine B, except at 90 percent power where the reverse occurs. An examination of engine A data, both untreated and with catalyst, and with 100 percent recirculation, indicates the following trends of emissions:

- As speed decreases; CO decreases, HC increases, and NO_x decreases.
- As power decreases; CO decreases, HC decreases, and NO_x decreases.

Computer sorts and plots were made to determine whether correlation exists in general between emission rates and specific fuel consumption (SFC). The results are shown in the plots of Figs. 6-1 through 6-6, for engines A and B, for CO, HC, and NO_x, respectively. In Figs. 6-5 and 6-6, the specific emission is plotted against the inverse of the SFC. The following indications are apparent:

- Emission rates are not much related to SFC.
- The use of a catalyst results in a very significant reduction in CO emission.
- The use of a catalyst results in a reduction in HC emission, but to a less significant degree than that which occurs in the case of CO.
- The use of a catalyst appears to result in slightly higher NO_x emissions. This observation is more readily seen by inspection of the raw data.

Examination of the data mass shows significant reduction in NO_x emission with the introduction of exhaust recirculation, but a corresponding increase in CO and HC emissions.

Appendix N shows computer-calculated values at an engine speed of 2,400 rpm, of the ratio of specific emission to SFC for all data points transmitted in Ref. 6-1. Appendix M shows the engine data used in these calculations. The wide variation in the values of this ratio demonstrates the poor correlation between specific emissions and SFC. Because of this poor correlation, further calculations of this nature were not made for the data from Refs. 6-2 and 6-3.

A computerized sort was made to examine the correlation of CO, HC, NO_x, and SFC to the measured air-fuel ratio. This sort is shown in Appendix O. Although some general trends for CO, HC, and NO_x are seen to occur with increasing air-fuel ratio, they are not similar for the three types of emission, nor are they dependent upon air-fuel ratio to the exclusion of other engine operating variables. The pronounced difference in emissions between engines A and B under identical operating conditions may be seen in this sort.

DETERMINATION OF PREFERRED OPERATING POINTS

As mentioned previously, there are no points at which values of the emissions simultaneously fell within the converted 1976 emission levels. Furthermore, the minima or near minima for the three emissions are not coincident. In an attempt to

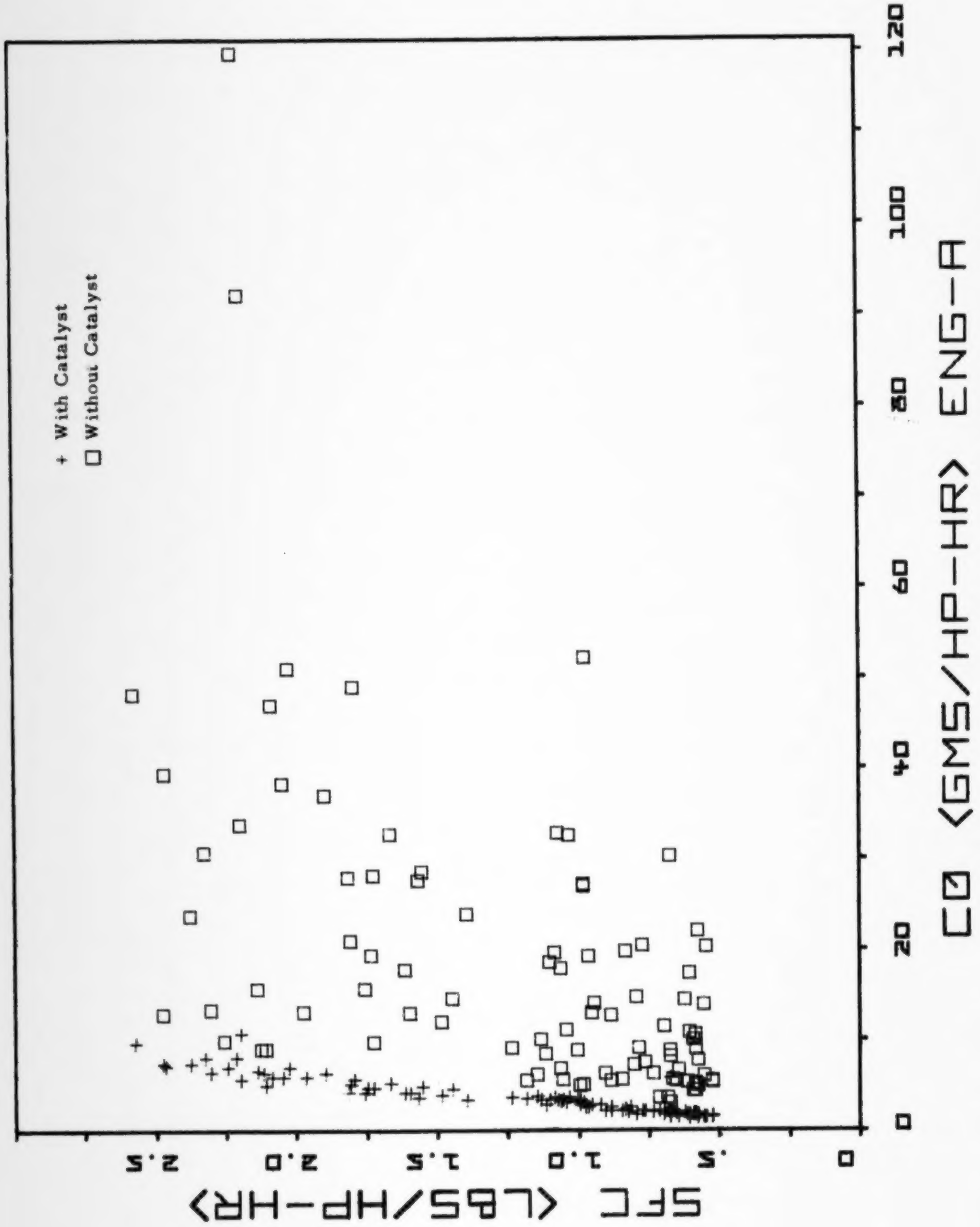

Fig. 6-1 Specific Fuel Consumption (SFC) Vs. CO Emissions – Engine A

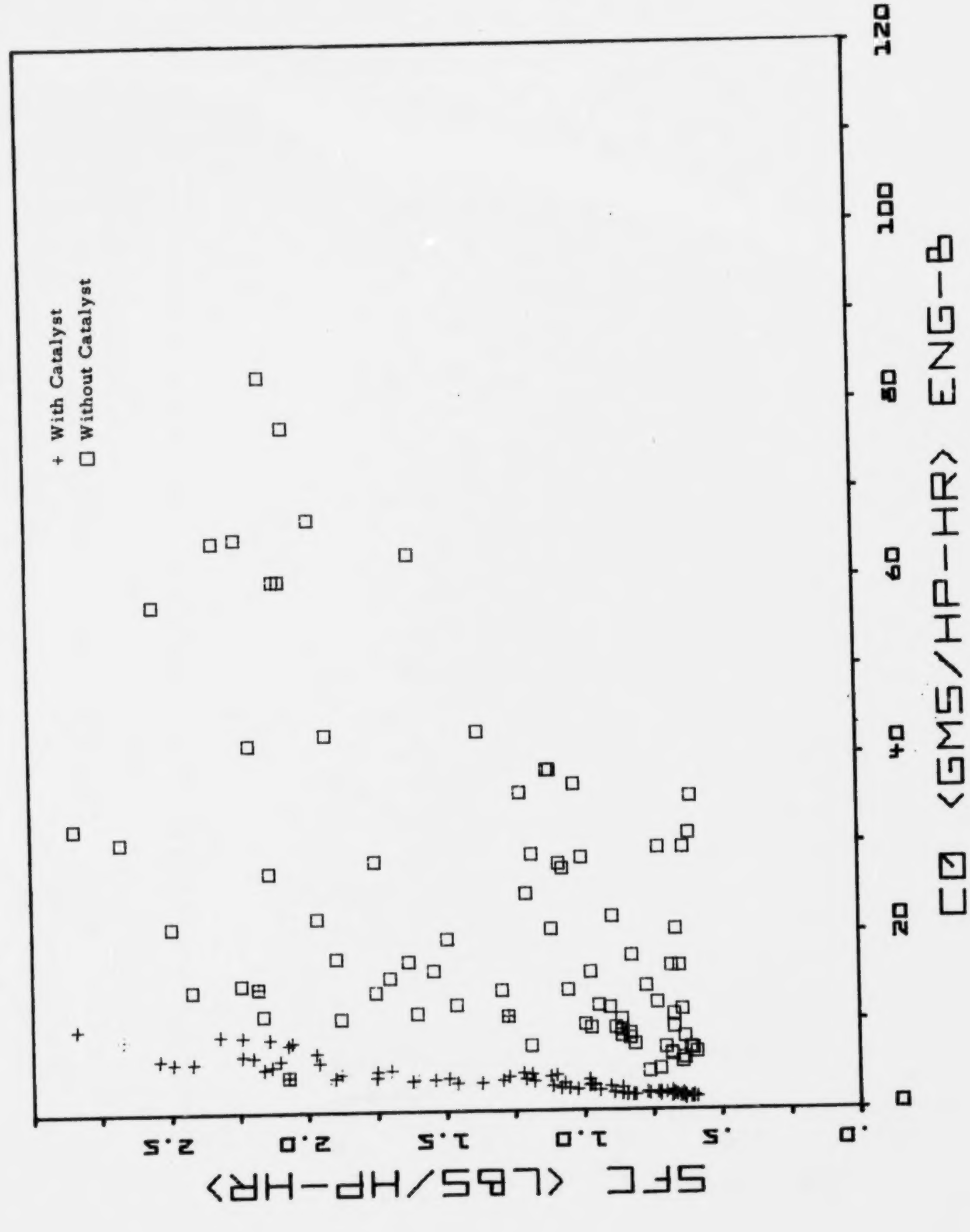

Fig. 6-2 Specific Fuel Consumption (SFC) Vs. CO Emissions – Engine B

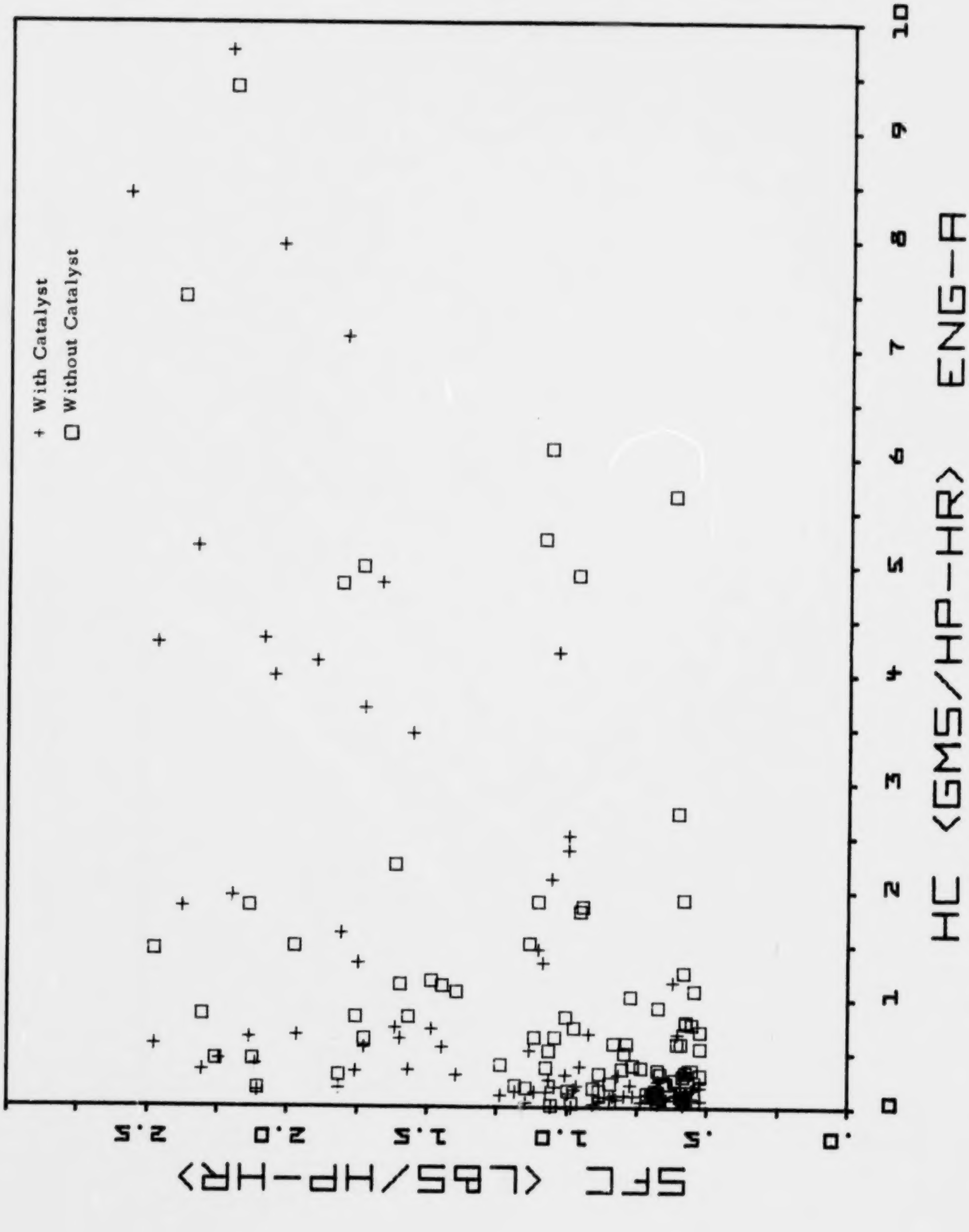

Fig. 6-3 Specific Fuel Consumption (SFC) Vs. HC Emissions – Engine A

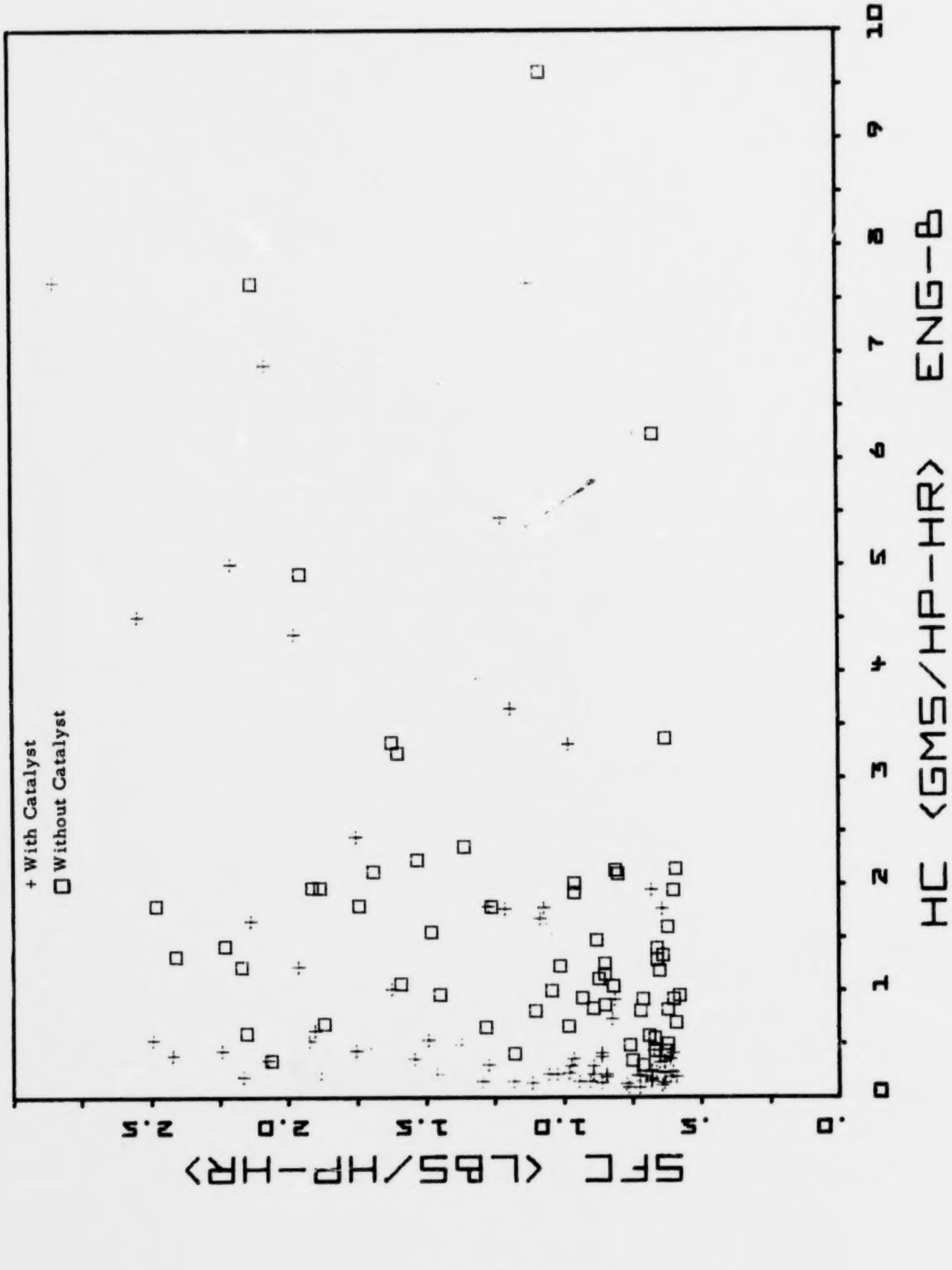

Fig. 6-4 Specific Fuel Consumption (SFC) Vs. HC Emissions – Engine B

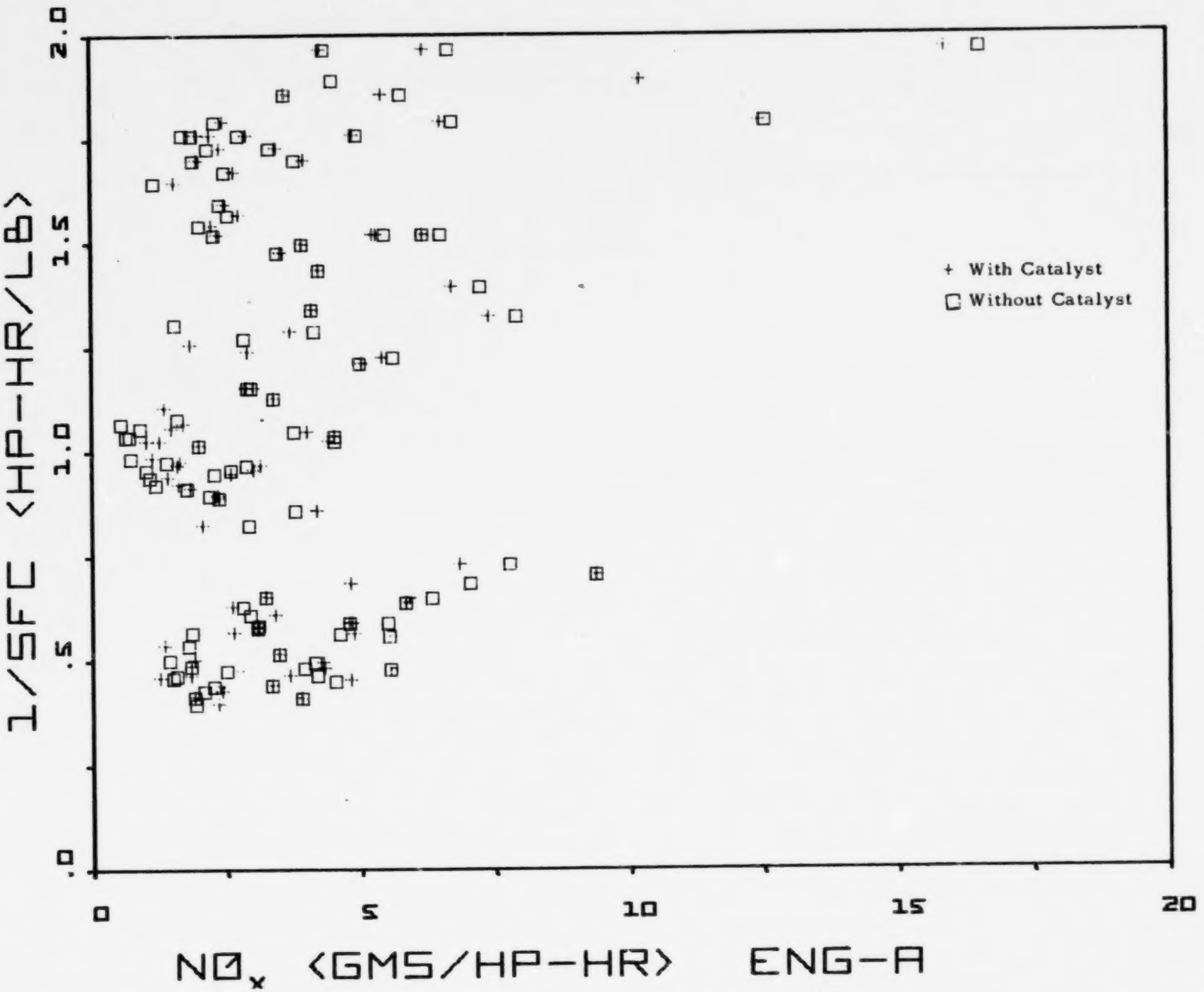

Fig. 6-5 Specific Fuel Consumption (SFC) Vs. NO_x Emissions – Engine A

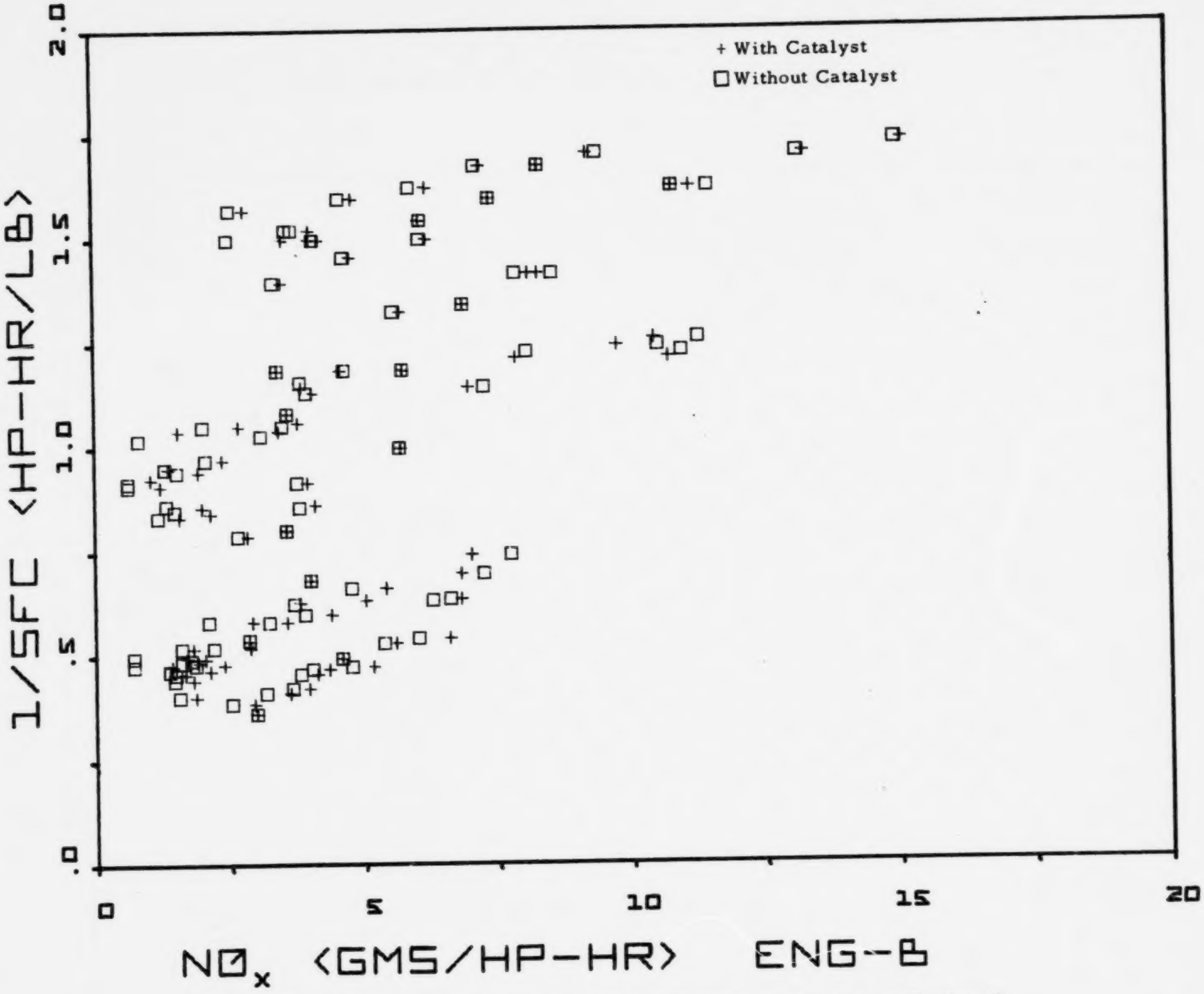

Fig. 6-6 Specific Fuel Consumption (SFC) Vs. NO_x Emissions – Engine B

gauge the total emissions, the concept of total weighted emissions (TWE) comparison was employed. In this concept, the value of each emission rate at a given test point was divided by its respective converted 1976 emission level, and the sum of the resultant three quotients was defined as the TWE for that test point. A comparison of the TWE was then made for all the test points.

Appendix P is a computer sort by percent power and speed in increasing order of TWE for the test points. Since the primary function of this sort was to identify the preferred operating points, upper limits were placed on the TWE values to be printed out. Therefore, only TWE values below 19 at 1,200 rpm flywheel speed, 12 at 1,600 rpm, and 17 at 2,400 rpm are shown. This makes possible the identification of preferred operating points for the engines, based on minimum TWE.

Contours of minimum TWE and contours of CO, HC, and NO_x at minimum TWE versus engine speed and power are shown for engine A in Figs. 6-7 through 6-10, and for engine B in Figs. 6-11 through 6-14. Each of these contours is based on only 12 data points; speeds of 1200, 1600, and 2400 rpm; and percent power values of 10, 25, 50, and 90 percent. The method of interpolation (and extrapolation to 800 rpm) involved, first, the use of a perfect fit binomial to interpolate (and extrapolate) specific emissions as a function of speed. Computer plots of these interpolation curves are given in Appendix Q.

A linear interpolation then was used between these curve values of emissions to yield emissions at the desired value of percent power. This interpolation method is illustrated graphically in Figs. 6-15 through 6-18; these are perspective views of the contours of Figs. 6-7 through 6-10, respectively.

ENGINE EMISSIONS OVER DYNO DRIVING CYCLE*

Minimum TWE values were used as a criterion to determine the proximity of approach to the converted 1976 emissions levels. For this purpose, the line of minimum TWE versus power for engine A over the power-speed-emissions plot shown in Fig. 6-10 was determined. The corresponding values of CO, HC, and NO_x for each power-speed

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*Cold start effects are not included.

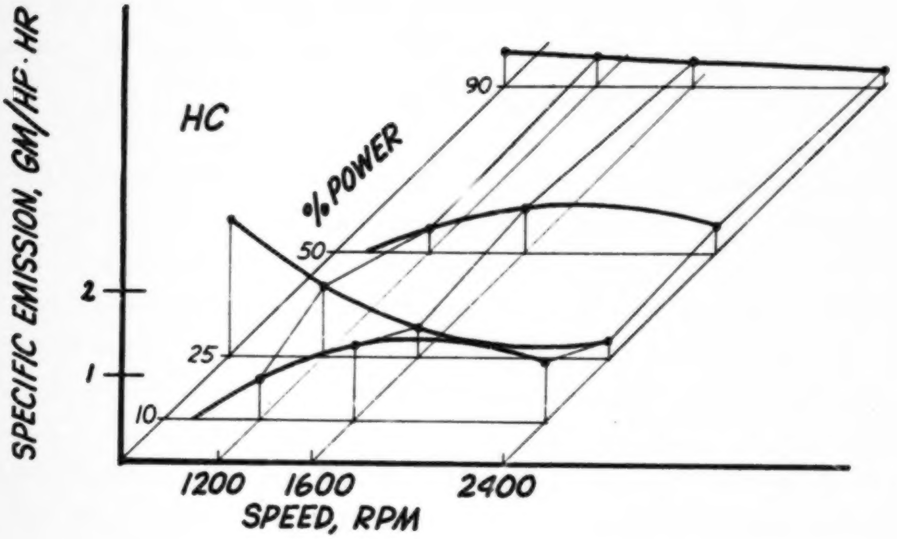

Fig. 6-7 HC Contour – Engine A

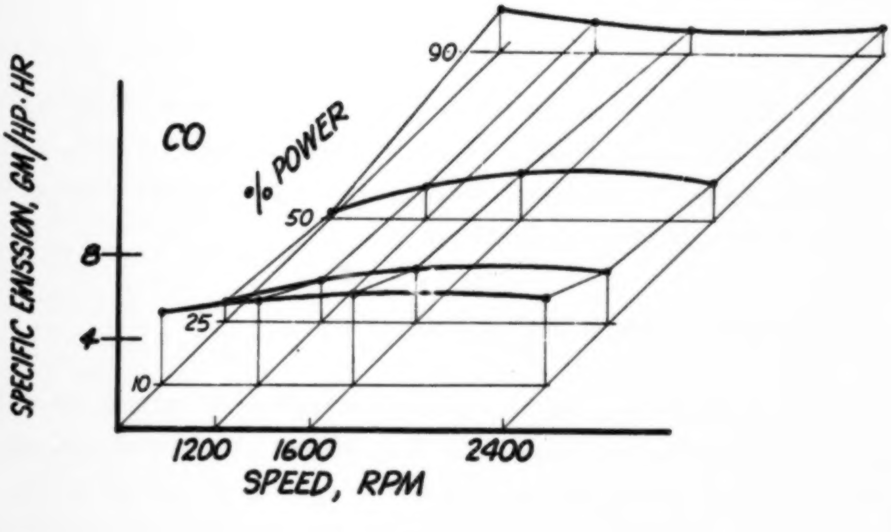

Fig. 6-8 CO Contour – Engine A

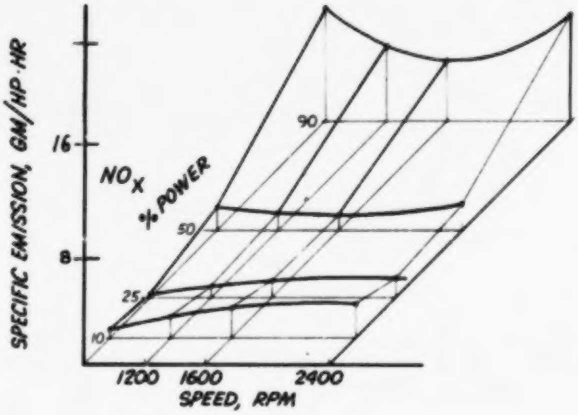

Fig. 6-9 NO_x Contour – Engine A

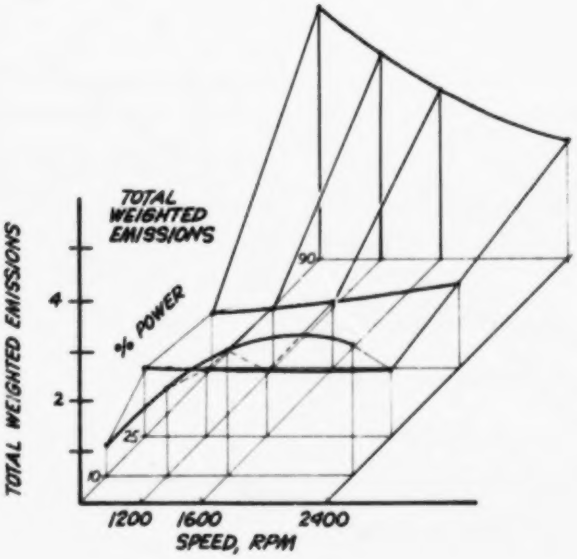

Fig. 6-10 TWE Contour – Engine A

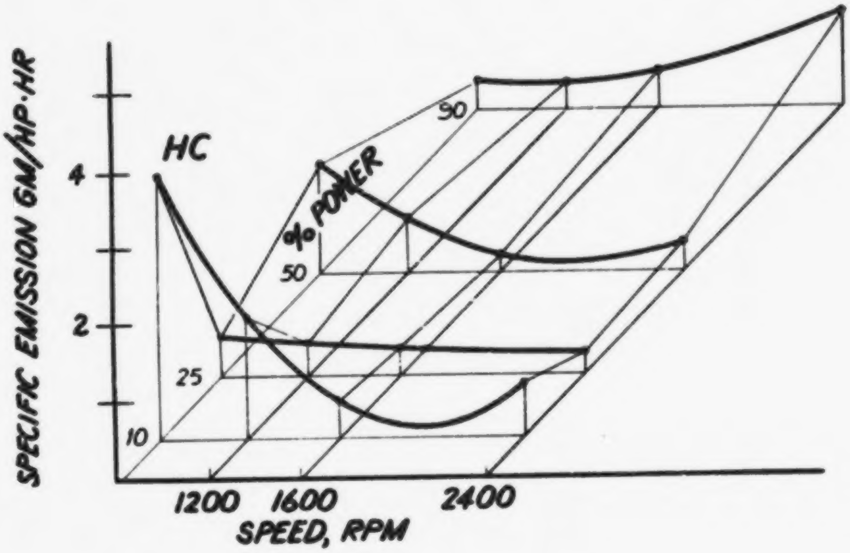

Fig. 6-11 HC Contour – Engine B

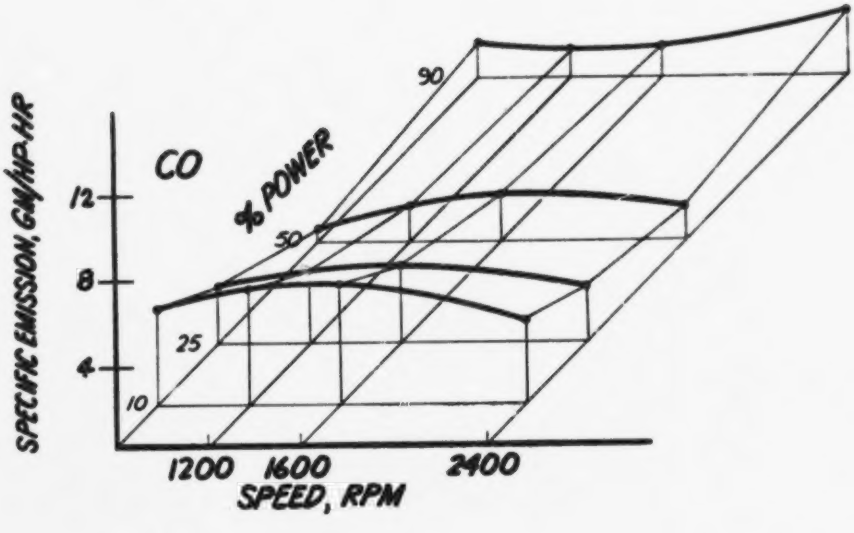

Fig. 6-12 CO Contour – Engine B

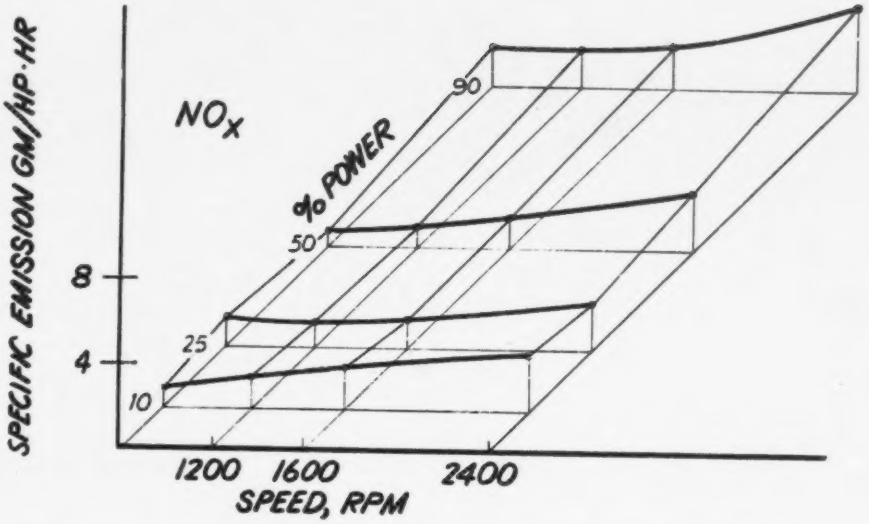

Fig. 6-13 NO_x Contour – Engine B

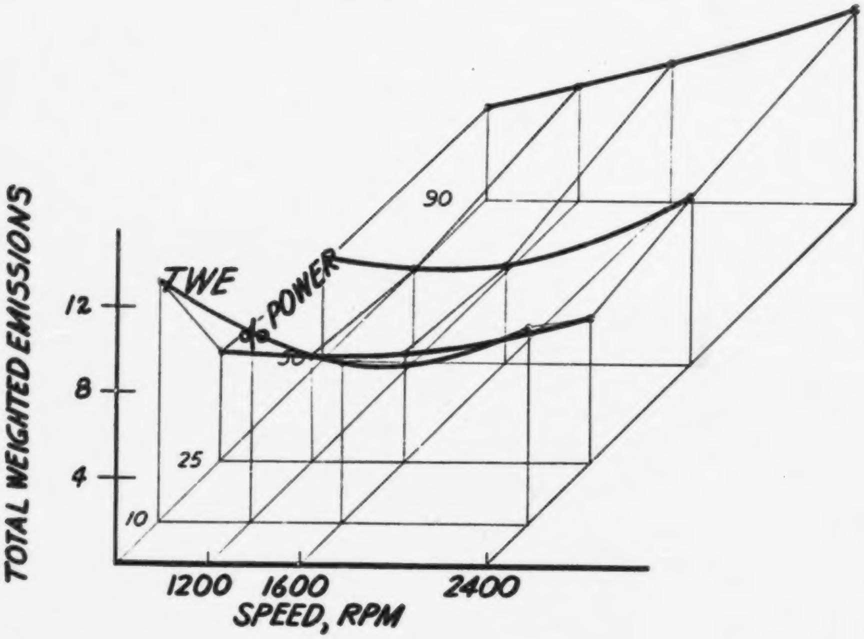

Fig. 6-14 TWE Contour – Engine B

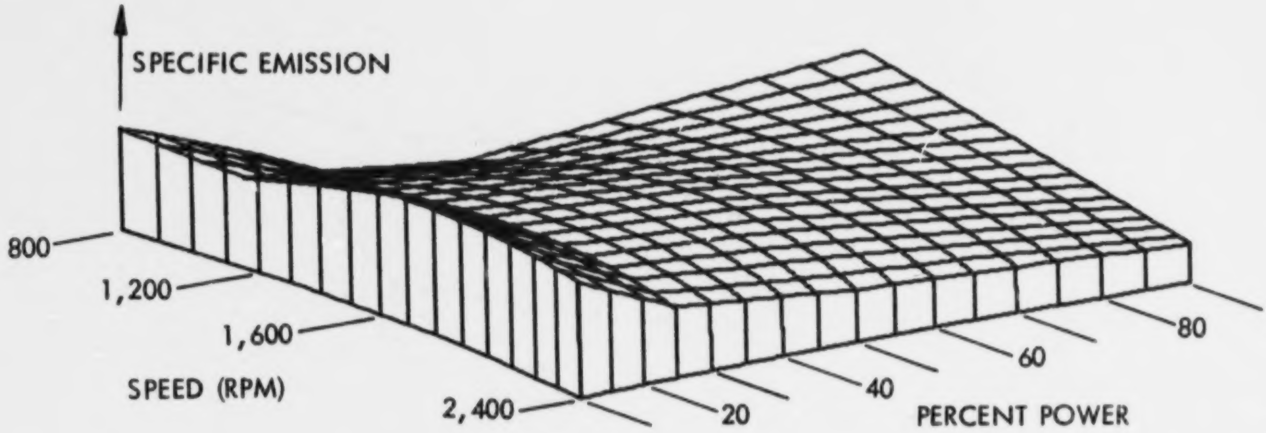

Fig. 6-15 CO Emission Contour, Engine A – Interpolation Perspective

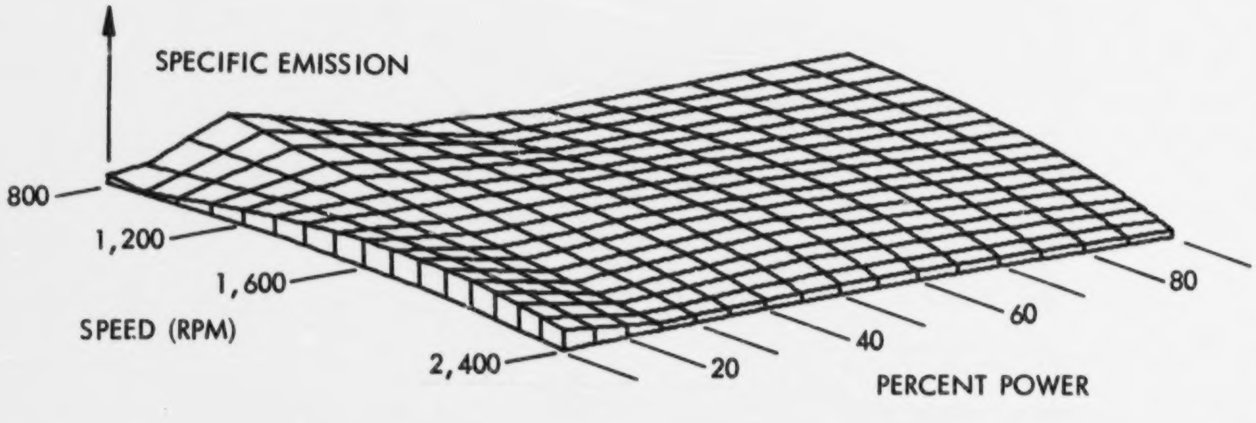

Fig. 6-16 HC Emission Contour, Engine A – Interpolation Perspective

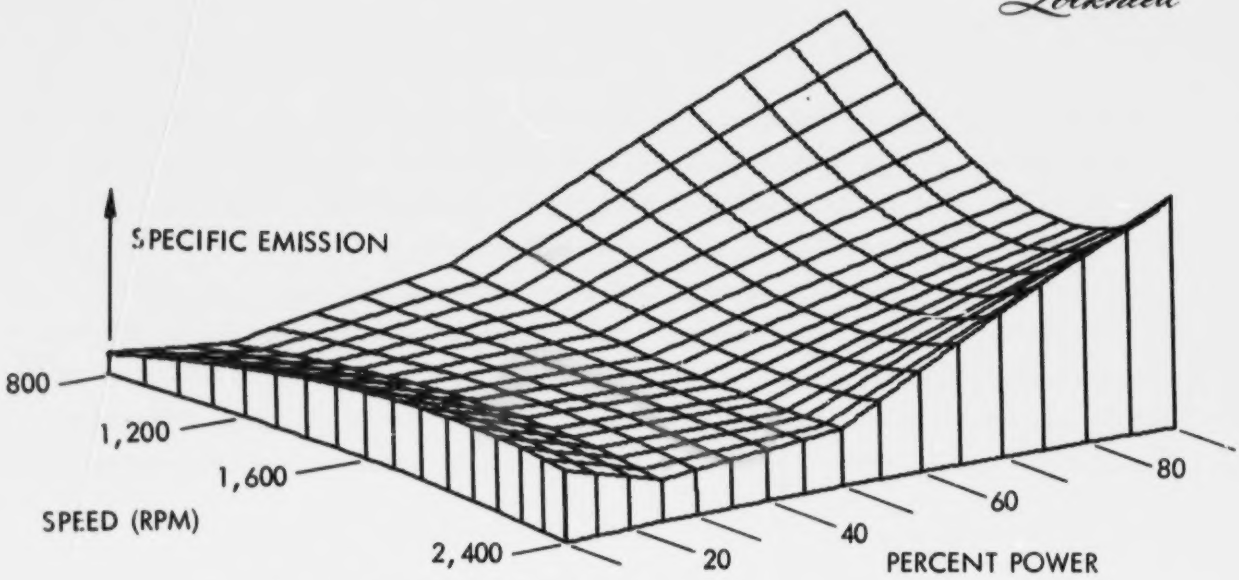

Fig. 6-17 NO_x Emission Contour, Engine A – Interpolation Perspective

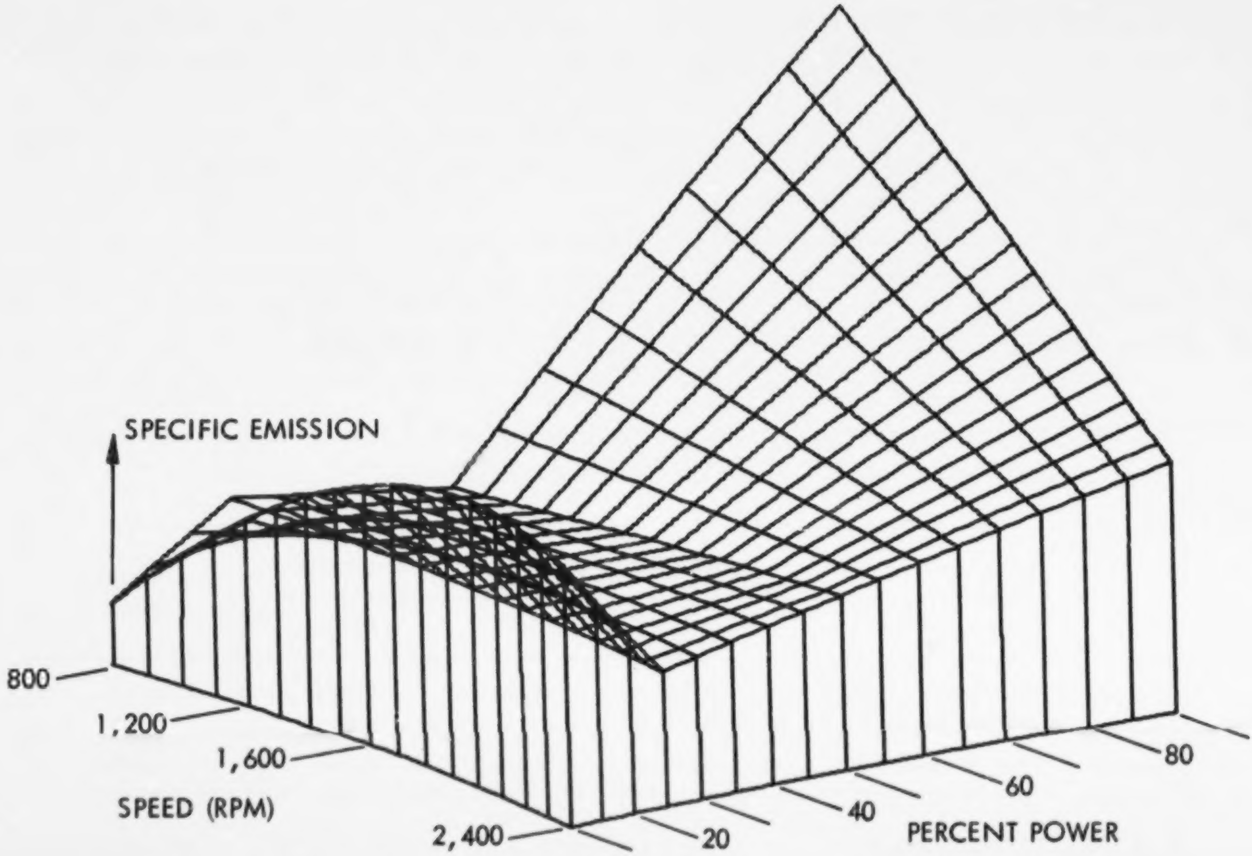

Fig. 6-18 Total Weighted Emissions Contour, Engine A – Interpolation Perspective

combination were then determined. The cumulative weight (g) of each emission constituent over the driving cycle was divided by driving-cycle total mileage, and then divided by the converted 1976 emission levels (g/mi) to obtain the ratio of each emission constituent of engine A to its respective 1976 level. A cumulative index of proximity to the standard was obtained by summing the individual constituent ratios and dividing by the number of constituents. Thus, if each of the three constituents (CO, HC, and NO_x) is exactly equal to its respective level, a value of 1.0 is obtained for the cumulative index, thus indicating equivalency to the 1976 levels. The higher the cumulative index value is above 1.0, the greater the cumulative emissions excess over the converted 1976 levels.

This procedure was followed for a 4,300-lb family car (see Appendix A) employing (1) a Sundstrand version 8C flywheel transmission, and (2) a conventional three-speed automatic transmission. In both cases there was an oxidation catalyst and exhaust gas recirculation, but no NO_x catalyst. The emission values over the driving cycle are as follows:

Drive	Constituent Concentration (g/mi)*		
	CO	HC	NO_x
Conventional, Three-Speed, Automatic Transmission	0.95	0.393	3.98
Flywheel Transmission	1.12	0.378	1.21

When these values are divided by the 1976 levels (see p. 6-6), the resulting constituent ratios and cumulative index values are as follows:

Drive	Constituent Ratio (g/mi) /(1976 level g/mi)			Cumulative Index
	CO	HC	NO_x	
Conventional, Three-Speed, Automatic Transmission	0.28	0.96	9.94	3.73
Flywheel Transmission	0.33	0.92	3.03	1.43

---

*No cold start.

The emission characteristics of the flywheel drive vehicle are seen in the lower NO_x and cumulative index values.

Because of lack of data, the following were neglected:

- Effects of engine transients inherent in conventional transmission operation
- Cold-start effects

CONCLUSIONS

The following conclusions have been reached as a result of the engine data analyses:

- There is little correlation between specific emissions and SFC.
- Between two engines of the same model there can be, under controlled test conditions, very significant differences in emission rates and trends.
- All minimum TWE points occur with the use of the Engelhard catalyst and at either 50 percent or 100 percent of maximum exhaust recirculation rate.
- Over the range of test conditions, with either engine, minimum TWE generally occurs at air-fuel ratios in the vicinity of stoichiometric.
- No single test condition resulted in emissions rates that satisfied the 1976 requirements.
- When using the hybrid drive system over the dyno driving cycle, theoretical emissions characteristics are significantly lower than such theoretical characteristics when the conventional three-speed automatic transmission is employed.
- Engine data with better resolution might well reveal areas of emissions. (The data interpolation hither-to employed is believed to be conservative.)

RECOMMENDATIONS

A survey of the points of minimum TWE and of "second-best" points, as revealed by Appendix P, and a review of the raw data corresponding to these points, suggests further investigation at other speeds and power levels near the estimated points of minimum TWE. For these points, it is recommended that the range of exhaust gas recirculation rates of 0, 25, 50, 75, and 100 percent of maximum be investigated.

Investigation of air-fuel ratios below stoichiometric would seem to be indicated, but communication with PRC reveals that lower air-fuel ratios would be incompatible with the capabilities and the limits of the Engelhard catalyst.

Section 7
TECHNOLOGY APPLICATION

Many techniques directly usable in activities utilizing a wide range of advanced automotive drive systems have been developed, demonstrated, and evaluated in the Flywheel Hybrid Drive Systems Study. These techniques may be applicable to other activities in the AAPS Program. These technologies (described in detail in preceding sections) are examined from the standpoint of continuing usefulness to EPA/OAP (and to other U. S. Government agencies) in areas other than the kinetic energy systems for which they were developed.

COMPUTER-AIDED EMISSION ANALYSIS

The methodologies and computer programs, as developed by LMSC in the preceding EPA/OAP contract (Ref. 1-1), augmented by the work described in Section 6 of this report are immediately applicable to a broad spectrum of automotive emission control programs. The existing techniques have proved their usefulness in engine emission analysis and mapping as well as in the simulated operation of various automotive drive configurations over the dyno cycle.

ENGINE EMISSION ANALYSIS

The meaningful redirection and analysis of the large mass of raw data from engine emission mapping tests (such as those performed by LMSC for the tests conducted by the U. S. Bureau of Mines, Petroleum Research Center, as described in Section 6) were useful in this study and may be useful in the study of any type of engine under consideration by EPA/OAP.

These existing techniques and programs can be used for rapid focusing of an emission analysis program on the most promising engine operating conditions for improvement in any particular emission as well as in total weighted emissions.

The interactive use of the LMSC methodology in a mapping program thus reduces the required number of measured engine operating points but provides, at the same time, a more precise map of the most desirable engine operating regions. In addition, the LMSC program can be used to obtain two- or three-dimensional plots of individual emissions or of weighted combinations of emissions. The computer-aided techniques are applicable to emissions analysis of any engine type (e.g., Otto, Diesel, Rankine, Brayton, or other types).

SIMULATED FEDERAL DRIVING CYCLE OPERATION

The computer programs which are now available at LMSC can be used to calculate the specific and weighted emissions resulting from the operation of any conventional or unconventional automotive propulsion system over the dyno cycle. The program is in such a form that the loading into the computer of engine emission maps, together with transmission and vehicle characteristics, will permit direct calculations of specific emissions (in terms of g/mi) and specific fuel consumption (SFC) for dyno operations. This program, however, would need modification to include the 1975 Federal Test Procedure (hot/cold weighting) and to estimate cold start effects.

Comparative and sensitivity studies can be readily conducted using this program to assess the operational benefits resulting from the following propulsion system variations and their many combinations and permutations:

- Engine types
- Engine operating conditions
- Exhaust conditioning
- Transmission characteristics
- Vehicle weight, rolling resistance, and drag
- Vehicle accessories
- Fuel types

The LMSC program can also provide specific emission and fuel consumption calculations for driving cycles and conditions other than those represented by the dyno cycle.

SAFETY ANALYSIS

The safety analysis methodology developed in the Flywheel Drive Systems Study involves the use of fault tree and gross hazard analysis (see Section 4). These techniques can be applied to any conventional or unconventional propulsion system. Extensive use of these techniques in automotive systems has been made by the U.S. Department of Transportation, National Highway Traffic Safety Administration (NHTSA). The application of fault tree and gross hazard analysis methodologies will eventually be required for all new vehicle systems which fall under NHTSA cognizance. On this basis, the methodologies and analysis techniques developed by LMSC for EPA/OAP can be applied directly to safety analysis for any unconventional automotive propulsion system. In addition, the technique of relative safety evaluation described in Section 4 is particularly useful in determination of the relative hazards associated with the modification of automotive systems by change to unconventional means of propulsion.

HIGH SPEED SEALS AND BEARINGS

The design studies and testing conducted on seals and bearings suitable for high-speed flywheels (described in Section 5) are directly applicable to unconventional propulsion systems in which high speed rotating equipment is utilized. The bearing and seal requirements of gas and steam turbines are similar to those analyzed for high energy density flywheels. In addition, the seal and bearing test techniques and testing fixtures developed by LMSC for the Flywheel Drive Systems Study are now available for quantitative performance evaluation and comparison of various types of seals and bearings.

This test capability provides a means for conducting rotational tests up to 36,000 rpm with controllable side loading and precise torque, speed, and temperature measurement.

BURST CONTAINMENT

The flywheel burst dynamics analysis and containment testing described in Section 3 has resulted in new insights and techniques for the positive containment of high speed rotating machinery. The applicability of these technologies to, for example, the Brayton and Rankine cycle turbine elements, is clear.

ENGINE FLYWHEELS

The computer-aided flywheel design methodology developed as part of the EPA/OAP flywheel programs appears to be useful in the design and optimization of torsional stabilizing flywheels for various unconventional engine systems. The use of the existing computer program for design of such flywheels can result in significant improvement in engine weight and performance by fully utilizing the flywheel material.

Section 8

CONCLUSIONS AND RECOMMENDATIONS

The overall conclusion of the Flywheel Drive Systems Study is that the flywheel drive continues to appear to be a technically feasible means of emission reduction for the family car. Computer-aided emissions analysis did not indicate that the flywheel drive system could meet future stringent requirements. On the basis of certain assumptions, NO_x emissions with the flywheel drive were less than one-third of those produced with the conventional automatic transmission. Nevertheless, the available data on engine emissions were not sufficient to permit an accurate evaluation of the flywheel drive as a cost-effective means of emission reduction. Additional engine emission measurements should be made with dynamometer simulation of engine load over the dyno cycle for a conventional automatic transmission and for various configurations of the flywheel transmission so as to provide an accurate determination of emission reductions. Development of flywheel drive transmissions should be postponed until more definitive results of the emission reduction potentials of the flywheel drive are obtained.

Specific conclusions and recommendations arising from this study are as follows:

(1) A comparative analysis of engine emissions with a flywheel drive, as contrasted with a conventional three-speed automatic transmission, shows that some emission reductions occur on a total emissions basis, but future emission levels were not met using these particular data.

(2) Fuel economy over the dyno cycle for the flywheel transmission should be roughly equivalent to that of a conventional transmission.

(3) The estimated cost of ownership, size, and weight of a family car flywheel drive fall within the established EPA/OAP Vehicle Design Goals.

(4) The projected production cost of complete family car flywheel assemblies is $100, plus or minus $15 depending on flywheel configuration; this is within previous estimates (Ref. 1).

(5) All the elements of a practical family car flywheel assembly are now available without further technology development.

(6) Early estimates of flywheel system losses as provided to the transmission contractors have been proved by hardware testing to be highly conservative. Flywheel windage, bearing, seal, and vacuum pump losses are substantially lower than earlier predictions.

(7) Prevention of flywheel burst due to overspeed can be obtained by allowing the flywheel to grow plastically into the containment ring. Total containment of a flywheel burst at energy levels representative of what might be the case for a full size vehicle were not successfully demonstrated with lightweight, low cost materials. Containment of a burst at 0.86 hp-hr was demonstrated with a 192-lb steel ring and at 0.46 hp-hr with a 167-lb composite ring.

(8) The flywheel drive can provide safe family car propulsion if enough care is taken in systems and component design.

(9) Additional engine emission measurements should be made with dynamometer simulation of engine load over the dyno driving cycle for both a conventional automatic transmission and for various configurations of the flywheel transmission so as to provide an accurate determination of emission reductions.

(10) Development of flywheel drive transmissions should be postponed until more definitive results of the emission reduction potentials of the flywheel drive are obtained.

Section 9

FUTURE PROGRAM PLANS

The results of the Flywheel Drive Systems Study show that the flywheel drive continues to be a technically feasible means of obtaining some emission reduction for the family car. However, sufficient engine emission data were not available to allow an accurate quantitative assessment of the reduction in engine emissions brought about by the employment of a flywheel drive. In order to judge whether further development of flywheel drives is justified, it is essential to gather and evaluate definitive data on engine emissions. Engine emission measurements should be made with dynamometer simulation of engine load over the dyno cycle for various configurations of a flywheel transmission and for a reference conventional automatic transmission. Following is a plan for a program to provide a valid determination as to the merit of continued development of the flywheel drive as a means of emission reduction for the family car.

FLYWHEEL DRIVE EMISSION STUDY PROGRAM

OBJECTIVE

The purpose of the program is to provide a sufficiently realistic and accurate quantitative assessment of the reduction in engine emission brought about by the employment of a flywheel drive so as to permit a valid determination regarding the merit of its continued development as a means of emission reduction for the family car.

METHOD

Measurement would be made of engine emissions using dynamometer-simulated dyno driving cycle loads. This approach will assure that such effects as cold start, transients, etc., will be taken into account.

DURATION

The program, as planned, would require an approximate 10-month effort.

TASKS

The following tasks would be undertaken:

(1) Conduct engine emission testing in conjunction with a computer-aided search for the best (lowest emission) engine steady-state operating points for three types of transmission – flywheel transmission, infinite ratio (no energy storage) transmission, and conventional automatic transmission. Conduct tests with and without one or more catalytic and/or thermal reactors

(2) Design, build, and test engine control system to regulate air-fuel ratio, spark timing, exhaust gas recirculation, and other (e.g., throttle delay) engine parameters

(3) Measure engine emissions over the dyno cycle with dynamometer-simulated loads for the conventional transmission without and with the control system developed under Task (2)

(4) Measure engine emissions over the dyno cycle with dynamometer-simulated loads for the flywheel transmission with various throttle delay time constants, and for the infinite ratio transmission using the control system developed under Task (2)

(5) Evaluate results of emission measurements to determine relative advantages of flywheel transmission, infinite ratio transmission, engine control system, and one or more exhaust reactors employed in various combinations.

Section 10
REFERENCES

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6-1 Environmental Protection Agency, Air Pollution Control Office, Emission Optimization of Heat Engine/Electric Vehicle, by J. Andon and I. R. Barpal, (APCO Project EHS-70-107), Ann Arbor, Michigan, January 28, 1971

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6-3 Letter (and attachments thereto) from R. D. Fleming, Bureau of Mines Petroleum Research Center, Bartlesville, Oklahoma, to J. Salihi, Environmental Protection Agency, Office of Air Programs, Ann Arbor, Michigan, November 16, 1971

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6-5 Federal Register, Vol. 35, 219, Part II, November 10, 1970

APPENDIXES

Appendix A

VEHICLE DESIGN GOALS

This appendix contains the Vehicle Design Goals – Six-Passenger Automobile, Rev. C, May 28, 1971, of the Advanced Automotive Power Systems Program of the Air Pollution Control Office, Environmental Protection Agency.

AIR POLLUTION CONTROL OFFICE

ADVANCED AUTOMOTIVE POWER SYSTEMS PROGRAM

"Vehicle Design Goals - Six Passenger Automobile"

(Revision C – May 28, 1971 – 11 Pages)

The design goals presented below are intended to provide:

A common objective for prospective contractors.

Criteria for evaluating proposals and selecting a contractor.

Criteria for evaluating competitive power systems for entering first generation system hardware.

Advisory criteria in such areas as rolling resistance, vehicle air drag etc. are included to assist the contractor.

The derived criteria are based on typical characteristics of the class of passenger automobiles with the largest market volume produced in the U. S. during the model years 1969 and 1970. It is noted that emissions, volume and most weight characteristics presented are maximum values while the performance characteristics are intended as minimum values. Contractors and prospective contractors who take exceptions must justify these exceptions and relate these exceptions to the technical goals presented herein.

1. Vehicle weight without propulsion system – W_o.

   W_o is the weight of the vehicle without the propulsion system and includes, but is not limited to: body, frame, glass and trim, suspension, service brakes, seats, upholstery, sound absorbing materials, insulation, wheels (rims and tires), accessory ducting, dashboard instruments and accessory wiring, battery, passenger compartment heating and cooling devices and all other components not included in the propulsion system. It also includes accessories such as, the air conditioner compressor, the power steering pump, and the power brakes actuating device.

   W_o is fixed at 2700 lbs.

2. Propulsion system weight – W_p.

   W_p includes the energy storage unit (including fuel and containment), power converter (including both functional components and controls) and power transmitting components to the driven wheels. It also includes the exhaust system, pumps, motors, fans and fluids necessary for operation of the propulsion system, and any propulsion system heating or cooling devices.

The maximum allowable propulsion system weight, W_{pm}, is 1600 lbs. However, light weight propulsion systems are highly desired. (Equivalent 1970 propulsion system weight with a spark ignition engine is 1300 lbs.)

3. Vehicle curb weight - W_c

$W_c = W_o + W_p$

The maximum allowable vehicle curb weight, W_{cm}, is 4300 lbs. (2700 + 1600 max. = 4300)

4. Vehicle test weight - W_t.

$W_t = W_c + 300$ lbs. W_t is the vehicle weight at which all accelerative maneuvers, fuel economy and emissions are to be calculated. (Items 8c, 8D, 8e).

The maximum allowable test weight, W_{tm}, is 4600 lbs. (2700 + 1600 max. + 300 = 4600).

5. Gross vehicle weight - W_g

$W_g = W_c + 1000$ lbs. W_g is the gross vehicle weight at which sustained cruise grade velocity capability is to be calculated. (Item 8f). The 1000 lbs. load simulates a full load of passengers and baggage.

The maximum allowable gross vehicle weight, W_{gm}, is 5300 lbs. (2700 + 1600 max. + 1000 = 5300).

6. Propulsion system volume - V_p

V_p includes all items identified under item 2. V_p shall be packagable in such a way that the volume encroachment on either the passenger or baggage compartment is not significantly different than today's (1970) standard full size family car. The propulsion system shall not violate the vehicle ground clearance lines as established by the manufacturer of the vehicle used for propulsion system/vehicle packaging. Additionally, the propulsion system shall not violate the space allocated for wheel jounce motions and vehicle steering. Necessary external appearance (styling) changes will be minor in nature. V_p shall also be packagable in such a way that the handling characteristics of the vehicle do not depart significantly from a 1970 full size family car.

The maximum allowable volume assignable to the propulsion system, V_{pm}, is 35 ft.^{3}.

7. Emission Goals

The vehicle when tested for emissions in accordance with the procedure outlined in the November 10, 1970 Federal Register shall have a weight of W_t. The emission goals for the vehicle are:

Hydrocarbons*	- 0.14 grams/mile maximum
Carbon monoxide	- 4.7 grams/mile maximum
Oxides of nitrogen**	- 0.4 grams/mile maximum
Particulates	- 0.03 grams/mile maximum

*Total hydrocarbons (using 1972 measurement procedures) plus total oxygenates. Total oxygenates including aldehydes will not be more than 10 percent by weight of the hydrocarbons or 0.014 grams/mile, whichever is greater.

**measured or computed as NO_2.

8. Start up, Acceleration, and Grade Velocity Performance.

a. Start up:

The vehicle must be capable of being tested in accordance with the procedure outlined in the November 10, 1970 Federal Register without special driver startup/warmup procedures.

The maximum time from key on to reach 65 percent full power is 45 sec. Ambient conditions are 14.7 psia pressure, 60°F temperature.

Powerplant starting techniques in low ambient temperatures shall be equivalent to or better than the typical automobile spark-ignition engine. Conventional spark-ignition engines are deemed satisfactory if after a 24 hour soak at -20°F the engine achieves a self-sustaining idle condition without further driver input within 25 seconds. No starting aids external to the normal vehicle system shall be needed for -20°F starts or higher temperatures.

b. Idle operation conditions:

The fuel consumption rate at idle operating condition will not exceed 14 percent of the fuel consumption rate at the maximum design power condition. Recharging of energy storage systems is exempted from this requirement. Air conditioning is off, the power steering pump and power brake actuating device, if directly engine driven, are being driven but are unloaded.

The torque at transmission output during idle operation (idle creep torque) shall not exceed 40 foot-pounds, assuming conventional rear axle ratios and tire sizes. This idle creep torque should result in level road operation in high gear which does not exceed 18 mph.

c. Acceleration from a standing start:

The minimum distance to be covered in 10.0 sec. is 440 ft. The maximum time to reach a velocity of 60 mph is 13.5 sec. Ambient conditions are 14.7 psia, 85° F. Vehicle weight is W_t. Acceleration is on a level grade and initiated with the engine at the normal idle condition.

d. Acceleration in merging traffic:

The maximum time to accelerate from a constant velocity of 25 mph to a velocity of 70 mph is 15.0 sec. Time starts when the throttle is depressed. Ambient conditions are 14.7 psia, 85° F. Vehicle weight is W_t, and acceleration is on level grade.

e. Acceleration, DOT High Speed Pass Maneuver:

The maximum time and maximum distance to go from an initial velocity of 50 mph with the front of the automobile (18 foot length assumed) 100 feet behind the back of a 55 foot truck traveling at a constant 50 mph to a position where the back of the automobile is 100 feet in front of the front of the 55 foot truck is, 15 sec. and 1400 ft. The entire maneuver takes place in a traffic lane adjacent to the lane in which the truck is operated. Vehicle will be accelerated until the maneuver is completed or until a maximum speed of 80 mph is attained, whichever occurs first. Vehicle acceleration ceases when a speed of 80 mph is attained, the maneuver then being completed at a constant 80 mph. (This does not imply a design requirement limiting the maximum vehicle speed to 80 mph.) Time starts when the throttle is depressed. Ambient conditions are 14.7 psia, 85° F. Vehicle weight is W_t, and acceleration is on level grade.

f. **Grade velocity:**

The vehicle must be capable of starting from rest on a 30 percent grade and accelerating to 15 mph and sustaining it. This is the steepest grade on which the vehicle is required to operate in either the forward or reverse direction.

The minimum cruise velocity that can be continuously maintained on a 5 percent grade with an accessory load of 4 hp shall be not less than 60 mph.

The vehicle must be capable of achieving a velocity of 65 mph up a 5 percent grade and maintaining this velocity for a period of 180 seconds when preceded and followed by continuous operation at 60 mph on the same grade (as above).

The vehicle must be capable of achieving a velocity of 70 mph up a 5 percent grade and maintaining this velocity for a period of 100 seconds when preceded and followed by continuous operation at 60 mph on the same grade (as above).

The minimum cruise velocity that can be continuously maintained on a level road (zero grade) with an accessory load of 4 hp shall be not less than 85 mph with a vehicle weight of W_t.

Ambient conditions for all grade specifications are 14.7 psia 85° F. Vehicle weight is W_g for all grade specifications except the zero grade specification.

The vehicle must be capable of providing performance (Paragraphs 8c, 8d, 8e 8f)within 5 percent of the stated 85° F values, when operated at ambient temperatures from -20° F to 105° F.

9. Minimum vehicle range:

Minimum vehicle range without supplementing the energy storage will be 200 miles. The minimum range shall be calculated for, and applied to each of the two following modes: 1) A city-suburban mode, and 2) a cruise mode.

Mode 1: Is the driving cycle which appears in the November 10, 1970 Federal Register. For vehicles whose performance does not depend on the state of energy storage, the range may be calculated for one cycle and ratioed to 200 miles. For vehicles whose performance does depend on the state of energy storage the Federal driving cycle must be repeated until 200 miles have been completed.

Mode 2: Is a constant 70 mph cruise on a level road for 200 miles.

The vehicle weight for both modes shall be, initially, W_t. The ambient conditions shall be a pressure of 14.7 psia, and temperatures of 60° F, 85° F and 105° F. The vehicle minimum range shall not decrease by more than 5 percent at an ambient temperature of -20° F.

For hybrid vehicles, the energy level in the power augmenting device at the completion of operation will be equivalent to the energy level at the beginning of operation.

10. **System thermal efficiency:**

System thermal efficiency will be calculated by two methods:

A. A "fuel economy" figure based on 1) miles per gallon (fuel type being specified) and 2) the number of Btu per mile required to drive the vehicle over the 1972 Federal driving cycle which appears in the November 10, 1970 Federal Register. Fuel economy is based on the fuel or other forms of energy delivered at the vehicle. Vehicle weight is W_t.

B. A "fuel economy" figure based on 1) miles per gallon (fuel type being specified) and 2) the number of Btu per mile required to drive the vehicle at constant speed, in still air, on level road, at speeds of 20, 30, 40, 50, 60, 70, and 80 mph. Fuel economy is based on the fuel or other forms of energy delivered at the vehicle. Vehicle weight is W_t.

In both cases, the system thermal efficiency shall be calculated with sufficient electrical, power steering and power brake loads in service to permit safe operation of the automobile. Calculations shall be made with and without air conditioning operating. The ambient conditions are 14.7 psia and temperatures of 60° F, 85° F and 105° F. Calculations shall be made with heater operating at ambient conditions of 14.7 psia and 30° F (18,000 Btu/hr).

11. **Air Drag Calculation:**

The product of the drag coefficient, C_d, and the frontal area, A_f, is to be used in air drag calculations. The product C_dA_f has a value of 12 ft^2. The air density used in computations shall correspond to the applicable ambient air temperature.

12. **Rolling Resistance:**

Rolling resistance, R, is expressed in the equation $R = W/65\ [1 + (1.4 \times 10^{-3}V) + (1.2\ 10^{-5}V^2)]$ lbs. V is the vehicle velocity in ft/sec. W is the vehicle weight in lbs.

13. Accessory power requirements:

The accessories are defined as subsystems for driver assistance and passenger convenience, not essential to sustaining the engine operation and include: the air conditioning compressor, the power steering pump, the alternator (except where required to sustain operation), and the power brakes actuating device. The accessories also include a device for heating the passenger compartment if the heating demand is not supplied by waste heat.

Auxiliaries are defined as those subsystems necessary for the sustained operation of the engine, and include condensor fan(s), combustor fan(s), fuel pumps, lube pumps, cooling fluid pumps, working fluid pumps and the alternator when necessary for driving electric motor driven fans or pumps.

The maximum intermittent accessory load, P_{aim}, is 10 hp (plus the heating load, if applicable). The maximum continuous accessory load, P_{acm}, is 7.5 hp (plus the heating load if applicable). The average accessory load, P_{aa}, is 4 hp.

If accessories are driven at variable speeds, the above values apply. If the accessories are driven at constant speed, P_{aim} and P_{acm} will be reduced by 3 hp.

14. Passenger comfort requirements:

Heating and air conditioning of the passenger compartment shall be at a rate equivalent to that provided in the present (1970) standard full size family car.

Present practice for maximum passenger compartment heating rate is approximately 30,000 Btu/hr. For an air conditioning system at 110° F ambient, 80° F and 40% relative humidity air to the evaporator, the rate is approximately 13,000 Btu/hr.

15. Propulsion system operating temperature range:

The propulsion system shall be operable within an expected ambient temperature range of -40° to 125° F.

16. Operational life:

The mean operational life of the propulsion system should be approximately equal to that of the present spark-ignition engine. The mean operational life should be based on a mean vehicle life of 105,000 miles or ten years, whichever comes first.

The design lifetime of the propulsion system in normal operation will be 3500 hours. Normal maintenance may include replacement of accessable minor parts of the propulsion system via a usual maintenance procedure, but the major parts of the system shall be designed for a 3500 hour minimum operation life.

The operational life of an engine shall be determined by structural or functional failure causing repair and replacement costs exceeding the cost of a new or rebuilt engine. (Functional failure is defined as power degradation exceeding 25 percent or top vehicle speed degradation exceeding 9 percent).

17. Noise standards: (Air conditioner not operating)

a. Maximum noise test:

The maximum noise generated by the vehicle shall not exceed 77 dbA when measured in accordance with SAE J986a. Note that the noise level is 77 dbA whereas in the SAE J986a the level is 86 dbA.

b. Low speed noise test:

The maximum noise generated by the vehicle shall not exceed 63 dbA when measured in accordance with SAE J986a except that a constant vehicle velocity of 30 mph is used on the pass-by, the vehicle being in high gear or the highest gear in which it can be operated at that speed.

c. Idle noise test:

The maximum noise generated by the vehicle shall not exceed 62 dbA when measured in accordance with SAE J986a except that the engine is idling (clutch disengaged or in neutral gear) and the vehicle passes by at a speed of less than 10 mph. the microphone will be placed at 10 feet from the centerline of the vehicle pass line.

18. Safety standards:

The vehicle shall comply with all current Department of Transportation Federal Motor Vehicle Safety Standards. Reference DOT/HS 820 083.

19. Reliability and maintainability:

The reliability and maintainability of the vehicle shall equal or exceed that of the spark-ignition automobile. The mean-time-between failure should be maximized to reduce the number of unscheduled service trips. All failure modes should not represent a serious safety hazard during vehicle operation and servicing. Failure propagation should be minimized. The power plant should be designed for ease of maintenance and repairs to minimize costs, maintenance personnel education, and downtime. Parts requiring frequent servicing shall be easily accessable.

20. Cost of ownership:

The net cost of ownership of the vehicle shall be minimized for ten years and 105,000 miles of operation. The net cost of ownership includes initial purchase price (less scrap value), other fixed costs, operating and maintenance costs. A target goal should be to not exceed 110 percent of the average net cost of ownership of the present standard size automobile with spark-ignition engine as determied by the U.S. Department of Commerce 1969-70 statistics on such ownership.

Appendix B

CHARACTERISTICS OF CONVENTIONAL AUTOMATIC TRANSMISSIONS

The EPA supplied characteristic curves for a conventional automatic transmission to be used as a comparative reference for candidate flywheel transmission designs. These original curves were reduced to equations by LMSC using computer curve-setting techniques and, from these equations, computer-plotted curves were made. These computer plotted curves, shown in Figs. B-1 through B-10, were then checked for accuracy against the original curves. The equations were used in the LMSC and transmission contractor computer programs.

A computer run was made for a 4,300-lb family car per the EPA "Vehicle Design Goals – Six Passenger Automobile" - Revision C over the DHEW Driving Cycle (Federal Register, Vol. 35, 219, Part II, November 10, 1970) using this reference conventional automatic transmission. The following average values were obtained:

Road Power = 14.12 hp
Transmission Input Power = 18.19 hp
Accessory Power = 3.23 hp
Engine Power = 21.42 hp

From these values, which represent the 808 seconds in the DHEW cycle during which positive (non-zero) horsepower is delivered to the road, the following efficiencies were calculated:

Average Efficiency of Transmission = 77.622927 percent
Average Efficiency from Engine to Road = 65.931863 percent

TYPICAL TORQUE CONVERTER
CHARACTERISTIC
"B CAR"

EFFICIENCY (Y) VS OUTPUT RPM (X)

EQUATIONS:

$0 \leq X \leq 1760$

$Y = D + AX + BX^2 + CX^3$

$D = -.056175873$

$A = .1553398$

$B = -.00008819296$

$C = .000000016201761$

$1760 \leq X \leq 4500$

$Y = A + \frac{B}{X}$

$A = 105.551$

$B = -28798.4$

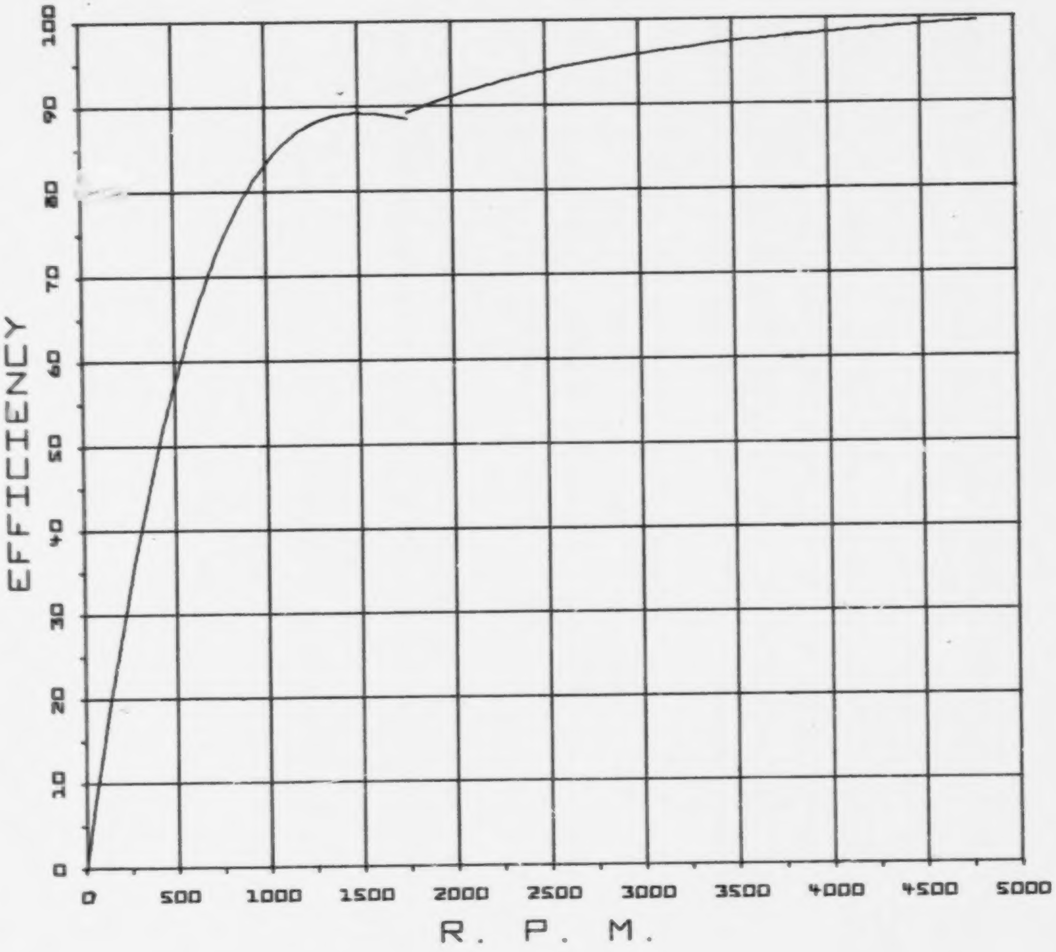
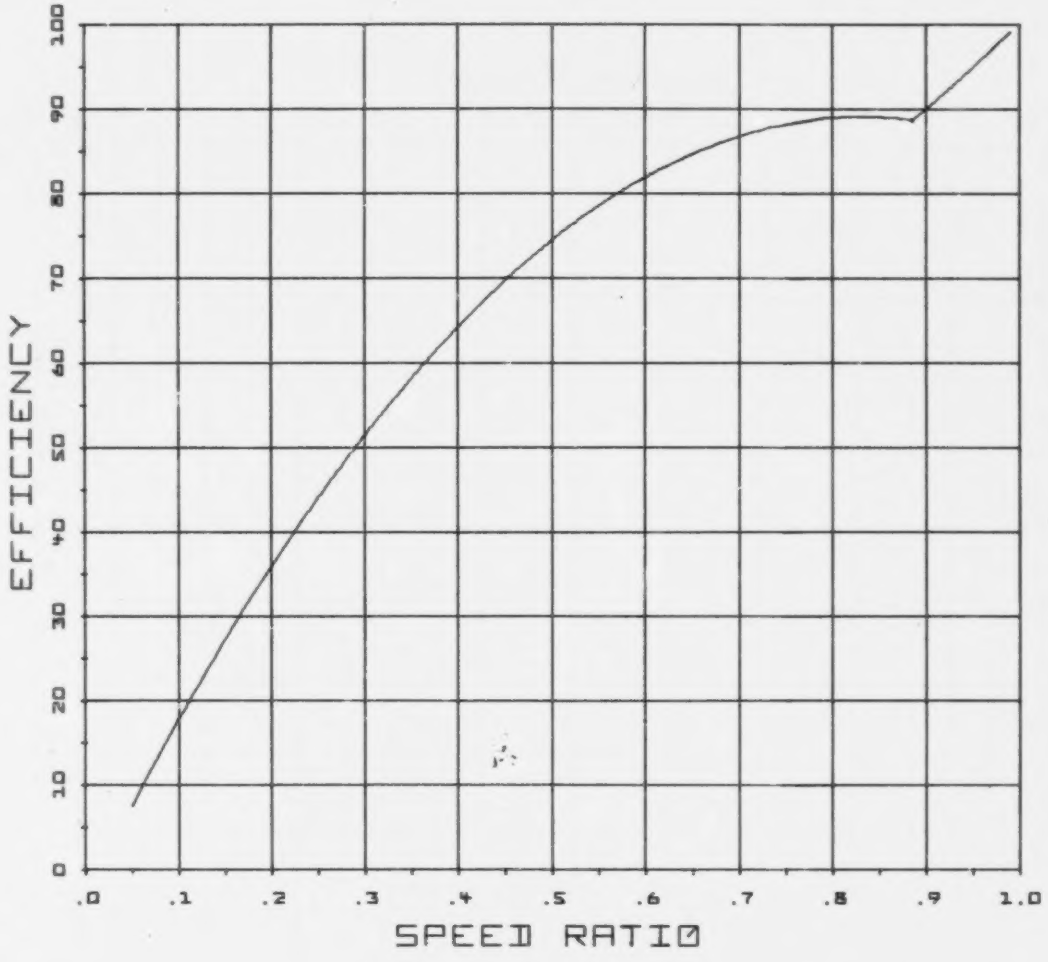


Fig. B-1 Typical Torque Converter Characteristic for B Car – Efficiency Vs. Output RPM



TYPICAL TORQUE CONVERTER
CHARACTERISTIC
"B CAR"

EFFICIENCY (Y) VS SPEED RATIO (X)

EQUATIONS:

$.05 \leq X \leq .885$

$Y = C + AX + BX^2$

$A = 221.44329$

$B = -132.73064$

$C = -3.20222103$

$.885 \leq X \leq .99$

$Y = Ae^{BX}$

$A = 34.318$

$B = 1.07122$

Fig. B-2 Typical Torque Converter Characteristic for B Car – Efficiency Vs. Output RPM

TYPICAL TORQUE CONVERTER
CHARACTERISTIC
"B CAR"

$\frac{\text{TORQUE OUT}}{\text{TORQUE IN}}$ (Y) VS SPEED RATIO (X)

EQUATIONS:

$.05 \le X \le .885$

$Y = A + BX$

$A = 2035.17$

$B = -1139.98$

$.885 \le X \le .99$

$Y = 1000$

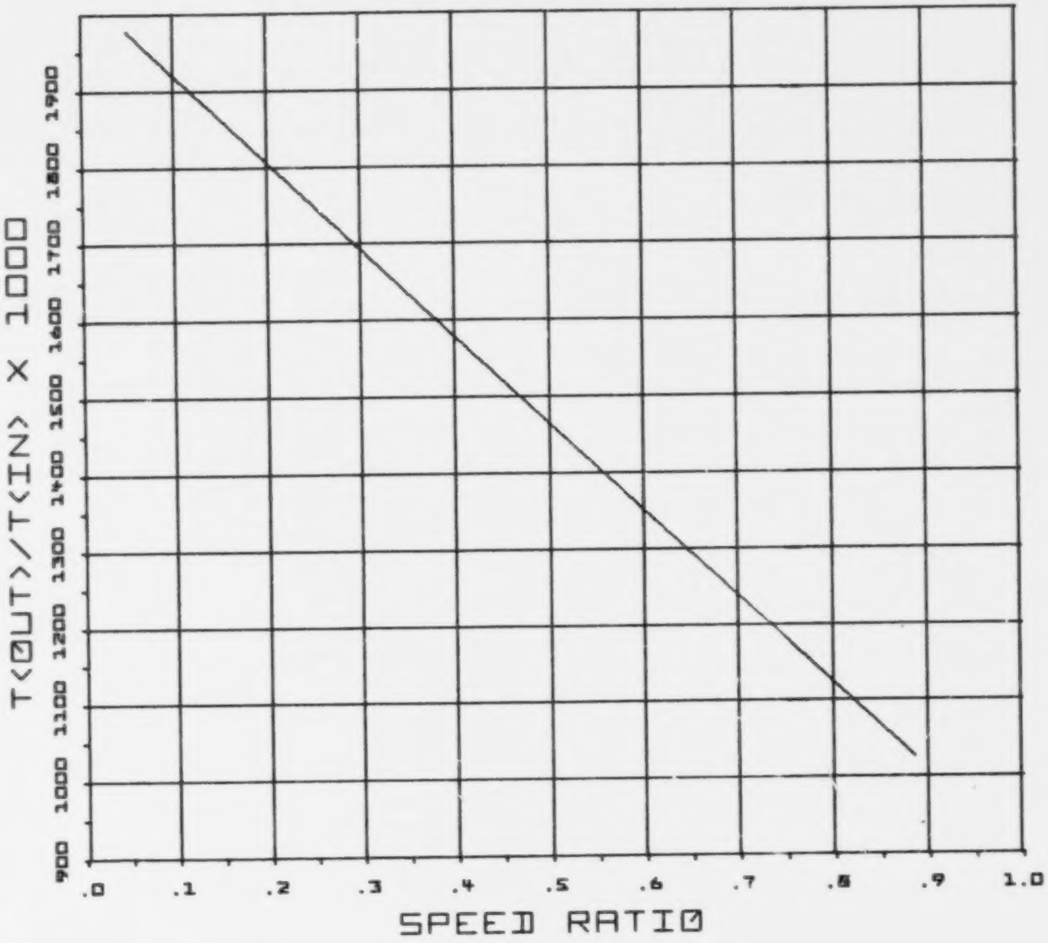
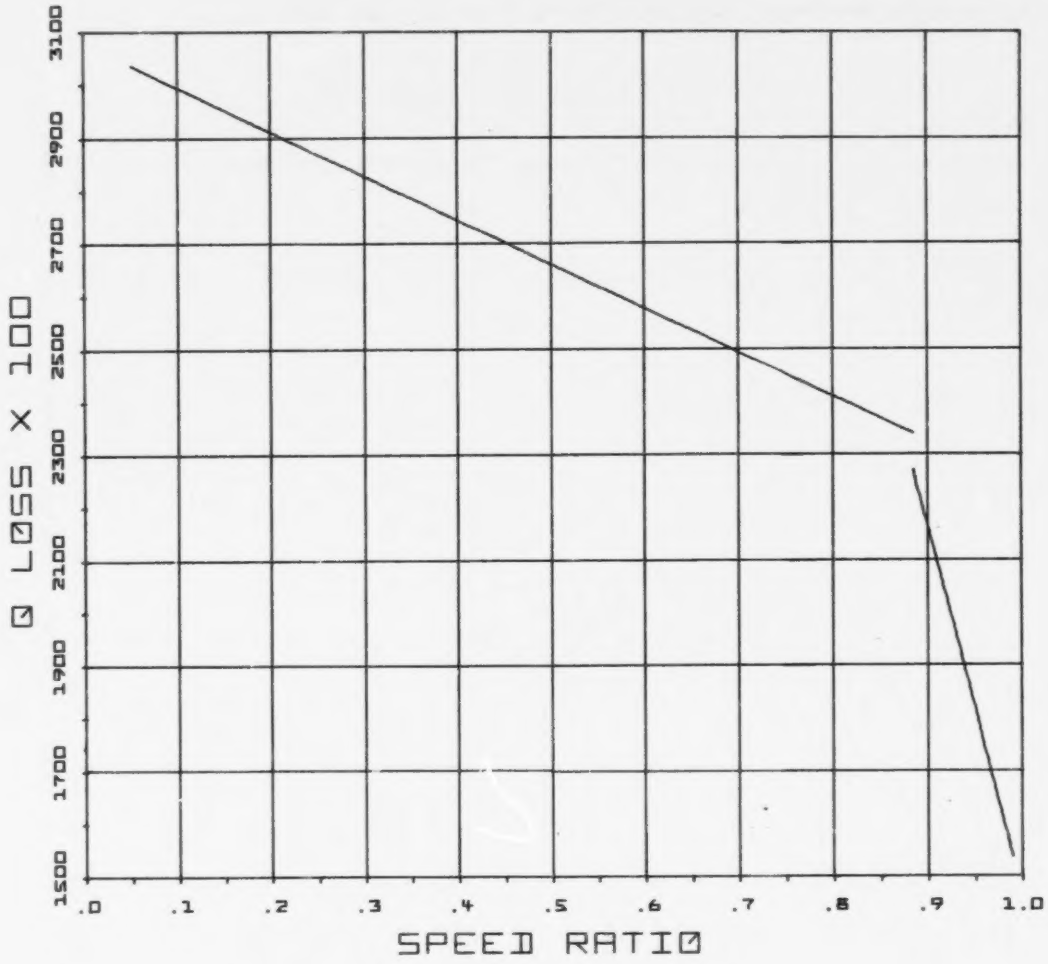


Fig. B-3 Typical Torque Converter Characteristic for B Car – (Torque Out/Torque In) Vs. Speed Ratio



TYPICAL TORQUE CONVERTER
CHARACTERISTIC
"B CAR"

Q LOSS (Y) VS SPEED RATIO (X)

EQUATIONS:

$.05 \le X \le .885$

$Y = A + BX$

$A = 3076.81$

$B = -832.612$

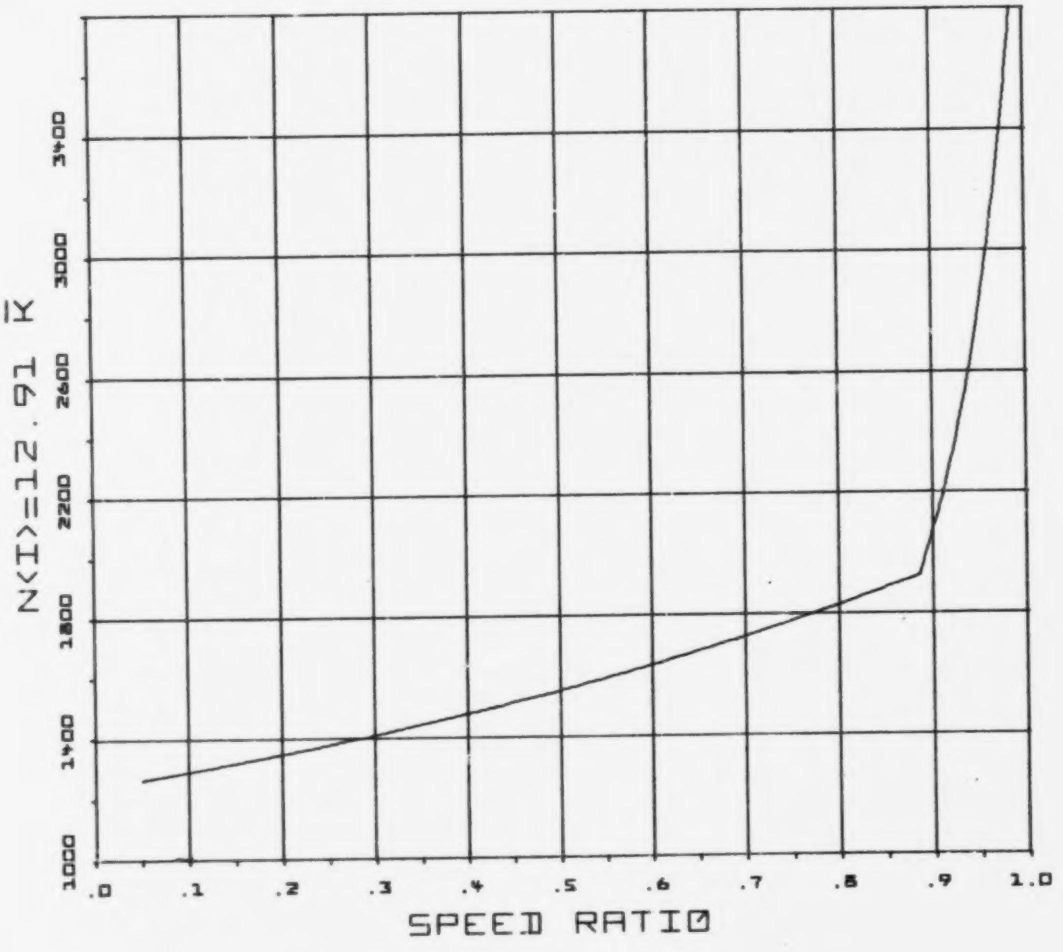
$.885 \le X \le .99$

$Y = A + BX$

$A = 8437.99$

$B = -6969.62$

Figure B-4 Typical Torque Converter Characteristic for B Car – Q Loss Vs. Speed Ratio



TYPICAL TORQUE CONVERTER
CHARACTERISTIC
"B CAR"

INPUT RPM (Y) = 12.91 K̄ (X)

EQUATIONS:

$.05 \leq X \leq .885$

$$Y = \frac{1}{A + BX}$$

A = .000807206

B = -.000325531

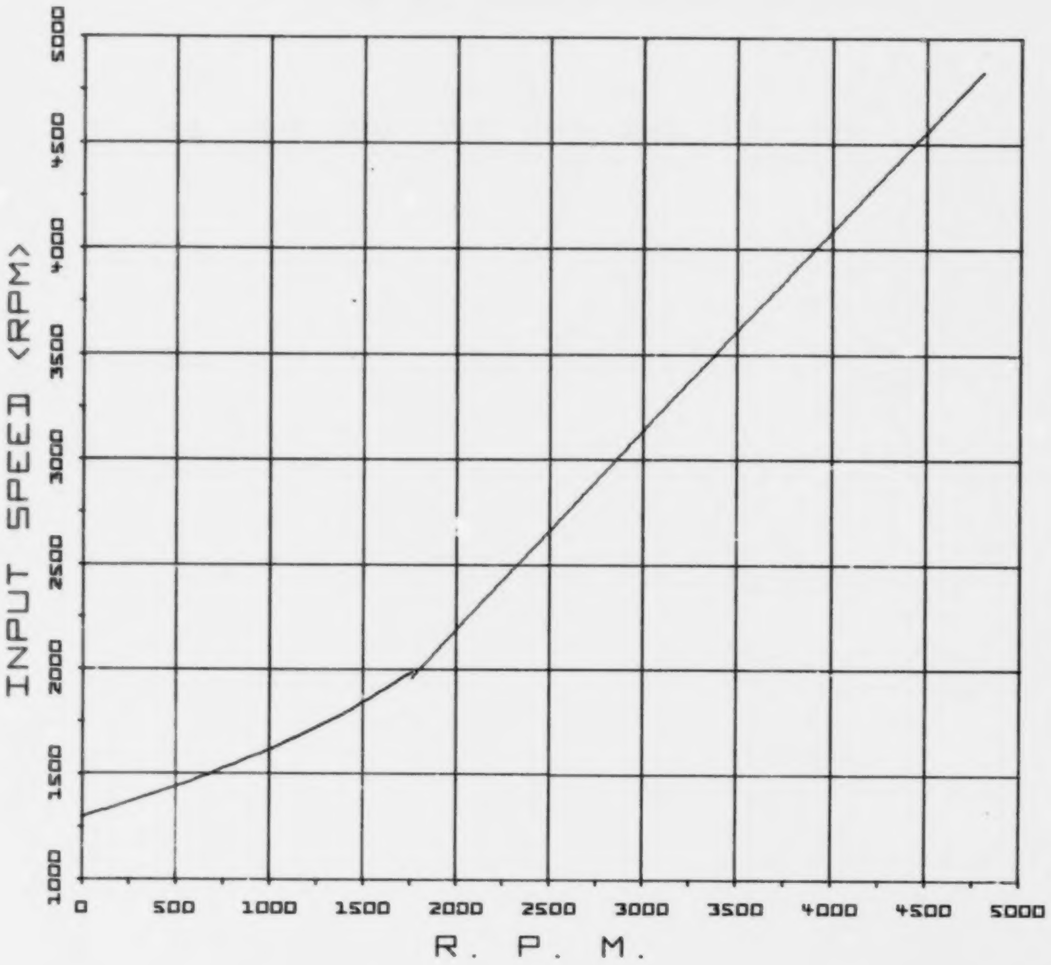
$.885 \leq X \pm .99$

$$Y = \frac{1}{A + BX}$$

A = .00274992

B = -.00252082

Fig. B-5 Typical Torque Converter Characteristic for B Car – Input RPM = 12.91 K



TYPICAL TORQUE CONVERTER
CHARACTERISTIC
"B CAR"

INPUT SPEED (Y) VS OUTPUT RPM (X)

EQUATIONS:

$0 \le X \le 1760$

$Y = \frac{1}{A + BX}$

$A = .000771222$

$B = -.000000152506$

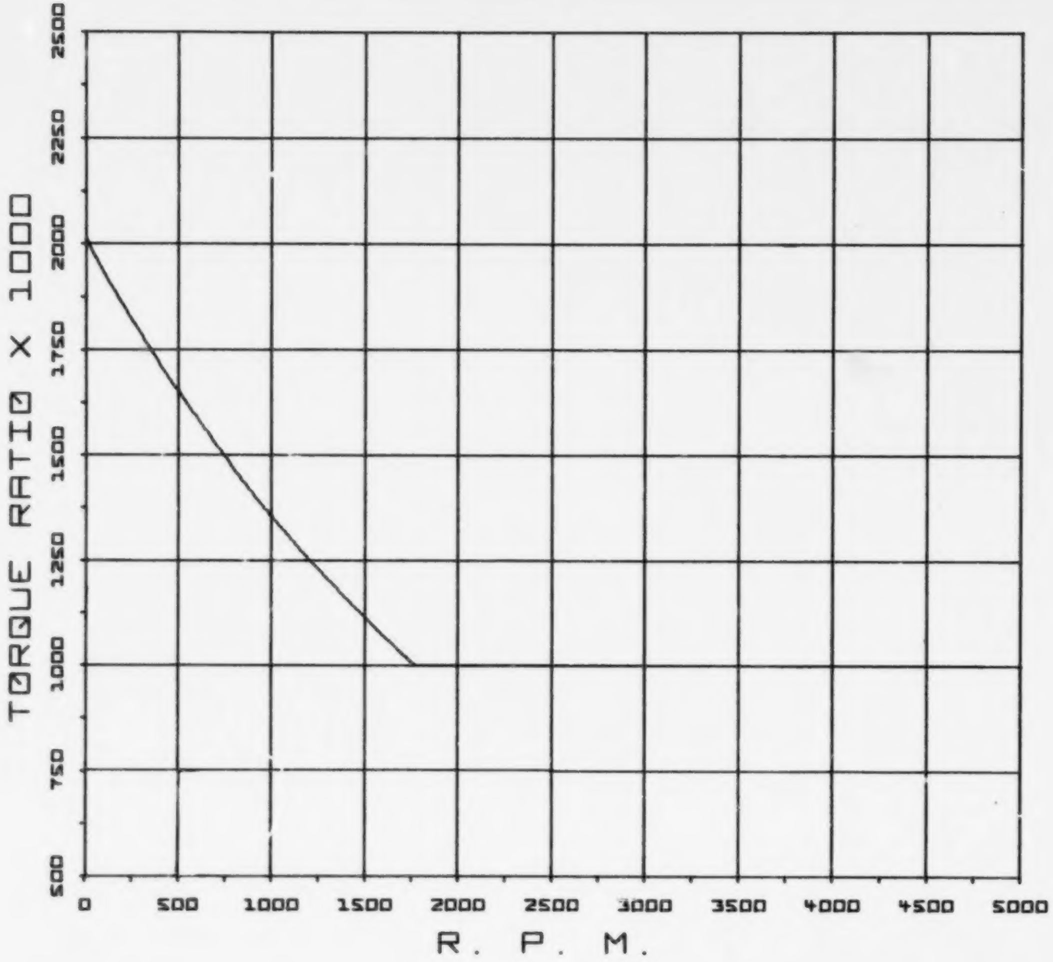
$1760 \le X \le 4500$

$Y = A + BX$

$A = 295.292$

$B = .946992$

Fig. B-6 Typical Torque Converter Characteristic for B Car – Input Speed Vs. Output RPM



TYPICAL TORQUE CONVERTER
CHARACTERISTIC
"B CAR"

TORQUE RATIO (Y) VS OUTPUT RPM (X)

EQUATIONS:

$0 \leq X \leq 1760$

$Y = Ae^{BX}$

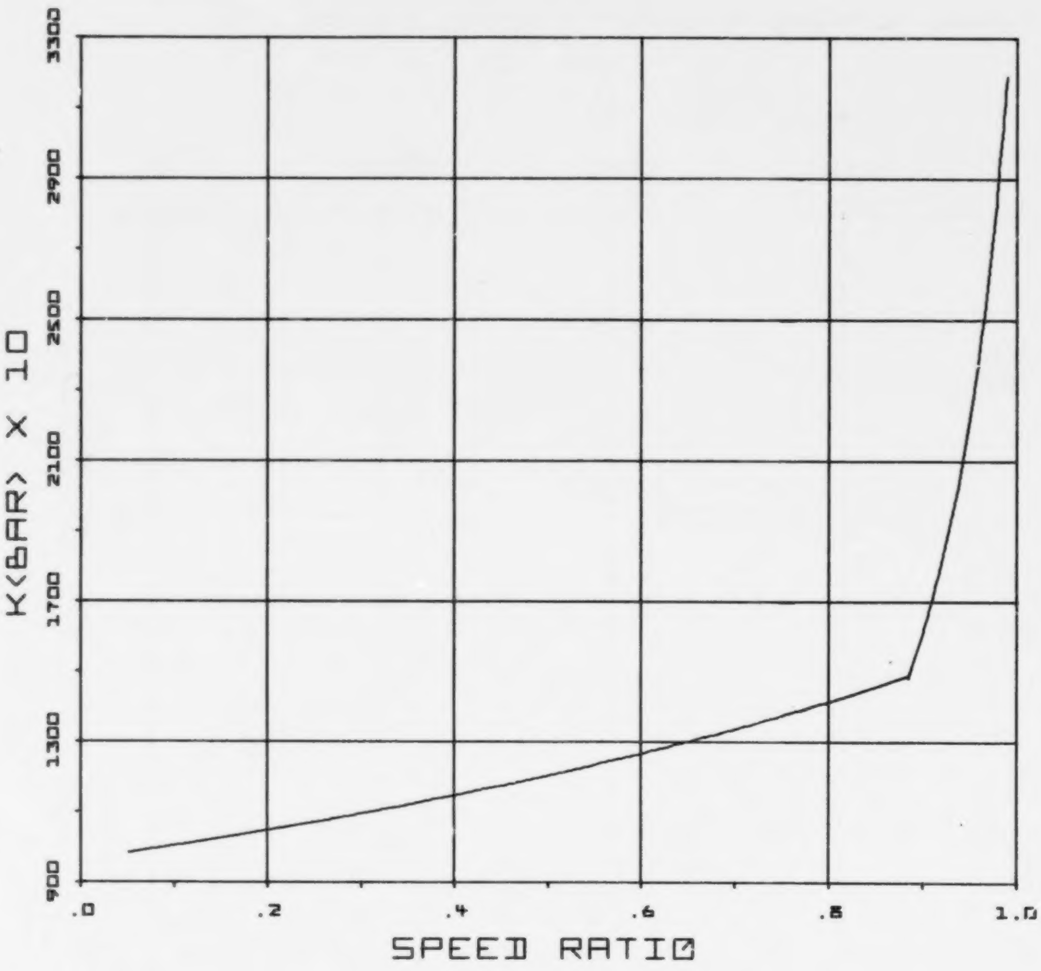
$A = 2011.12$

$B = -.00039502$

$1760 \leq X \leq 4500$

$Y = 1000$

Fig. B-7 Typical Torque Converter Characteristic for B Car – Torque Ratio Vs. Output RPM



TYPICAL TORQUE CONVERTER
CHARACTERISTIC
"B CAR"

$\bar{K}$ (Y) VS SPEED RATIO (Y)

WHERE:

$$K = \frac{\text{INPUT RPM}}{(\text{INPUT TORQUE})^{1/2}} (\text{DIAMETER})^{5/2}$$

$$(\text{DIAMETER})^{5/2} = 0.948 \text{ FT}$$

EQUATIONS: $.05 \leq X \leq .885$

$$Y = \frac{1}{A + BX}$$

A = .00103678

B = -.000412205

$.885 \leq X < .99$

$$Y = \frac{1}{A + BX}$$

A = .00371352

B = -.00343458

Fig. B-8 Typical Torque Converter Characteristic for B Car – K Vs. Speed Ratio

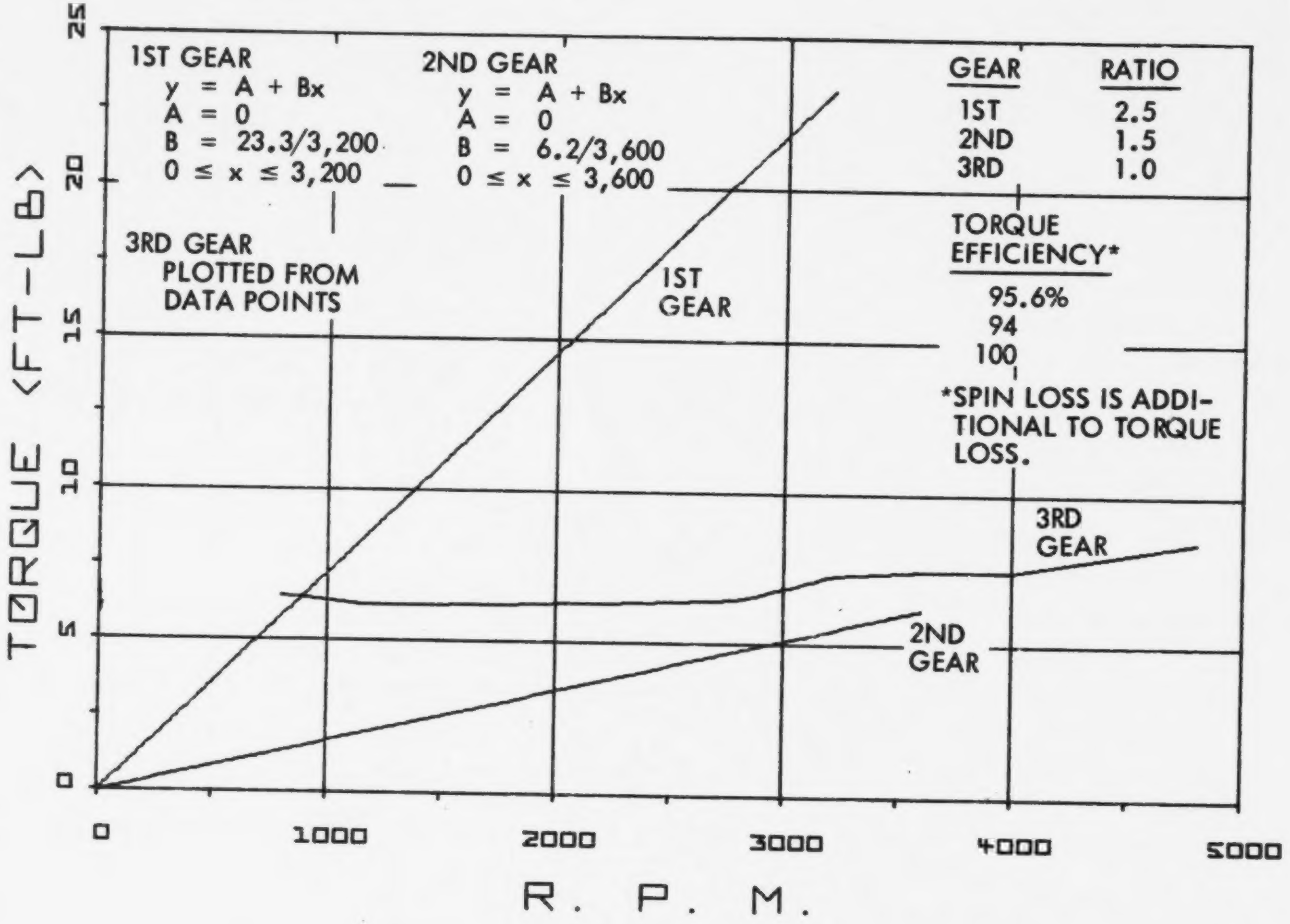


Fig. B-9 Transmission Spin Loss, Torque Vs. Propeller Shaft RPM – Typical B Car

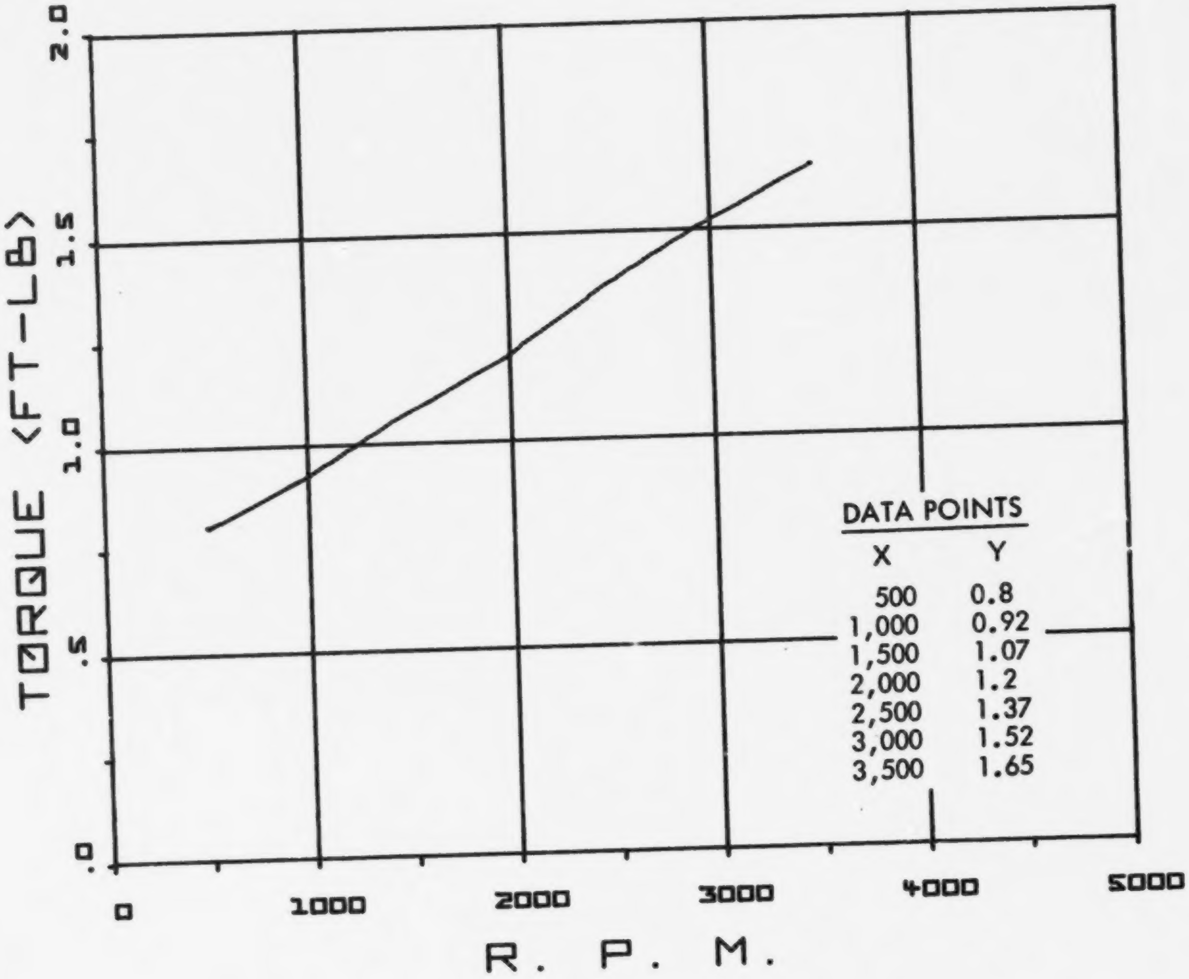


Fig. B-10 Axle Spin Loss Vs. Propeller Shaft RPM, Axle Torque Efficiency = 96 Percent above 25 mph – Typical B Car

Appendix C
COMPUTER PROGRAM DESCRIPTIONS

In the course of the Flywheel Drive Systems Study for the EPA, a number of computer programs were written, and several of the more significant of these programs are described in this appendix. They are written in BASIC for use with a time-sharing computer setup. In addition to these programs, standard programs for statistical analysis, data sorting, curve plotting, and curve fitting were also employed.

PROGRAM NAME: /5.0 MANEUVER/

SIZE

Approximately 10,000 Characters

DATA INPUTS

Constant Data

(See Fig. C-1.)

Profile

- Acceleration braking or cruise indicator
- Percent of maximum acceleration or braking potential
- Time to continue in this mode (sec); or velocity to be achieved in this mode (mph); or distance to be covered in this mode (ft)
- Grade (%)
- Increment for program execution (mph except for cruise which is sec)
- Increment for printing of program outputs
- Pause after each increment indicator

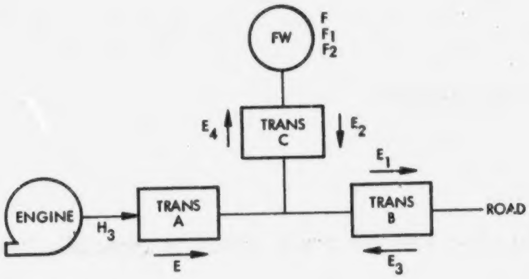
PROGRAM FUNCTIONS AND OUTPUTS

Computes incremental acceleration, velocity, tractive effort, road horsepower, engine horsepower, cumulative distance traveled, and flywheel energy.

COMMENTS

This program may be run in single or multiple increments from a terminal or it may be run automatically from a profile data file. In either case, it may be interrupted and continued with changes. Program validation procedures have been included to check for inconsistencies (e.g., actual deceleration of the vehicle such as might result from climbing a steep grade with insufficient power input when acceleration is specified). Provisions are also made to allow a vehicle to "accelerate" while braking such as would occur on a downhill run with light braking pressure, and for slowdown while applying low power inputs.

The outputs of this program are sufficient to provide data as desired (e.g., fuel consumption, specific emissions).



Inputs Required

Constants	**Units**
F = initial FW contents	kWh
F_1 = maximum FW contents	kWh
F_2 = minimum FW contents	kWh

Constants or Equations	
H_3 = engine output	inst. hp
E = trans. (A) efficiency	%/100
E_1 = trans. (B) efficiency out	%/100
E_2 = trans. (C) efficiency out	%/100
E_3 = trans. (B) efficiency in	%/100
E_4 = trans. (C) efficiency in	

(Normally only two transmissions are used, $E = 1$ for the other.)

Variables that equations can be a function of:

H_1 = instanteous horsepower at road	ft/sec
V_4 = average velocity of vehicle	ft/sec^2
A_1 = average acceleration	lb
R_1 = rolling resistance	lb
D_1 = aerodynamic drag	lb
G_1 = grade	%
H_2 = maximum engine output	inst. hp
F = flywheel contents	kWh
P_1 = percent of maximum road horsepower requested	%/100
H = maximum road horsepower	inst. hp

Fig. C-1 Maneuver Program

PROGRAM NAME: /7.0 TRANTEST/

SIZE

5376 Characters (plus merged program which is typically 5 to 7,000 additional characters)

DATA INPUTS

Variable	Unit
Weight	lb
Frontal Area	ft^2
Drag Coefficient	
Fuel Density	lb/gal

FILE INPUTS

Profile

A sequential file containing elapsed time, acceleration, acceleration type (constant horsepower or constant acceleration), and grade for trip profile

Specific Fuel Consumption

A random access file containing SFC as a function of rpm and horsepower

/7.0 Tran XXX/

A program file merged with the BAVE program before the run; contains the following:

Instruction No. Range	Contents
700 to 999	Constants to define efficiency and curves
6000 to 6999	Efficiency and "horsepower-into-transmission" calculation
7000 to 7999	Engine rpm calculation
8000 to 8990	Accessory and flywheel loss calculations

PROGRAM FUNCTIONS

Develops incremental and cumulative SFC, miles/gallon of fuel

PROGRAM OUTPUTS

Output for each second

- Time (sec)
- Acceleration (mph/sec)
- Velocity (mph)
- Distance traveled (ft)
- Road horsepower
- Transmission efficiency (%)
- Engine horsepower
- Engine speed (rpm)
- SFC (lb/hp-hr)
- Cumulative fuel (lb)
- Instantaneous consumption (mi/gal)
- Cumulative consumption (mi/gal)

PROGRAM NAME: /7.1 EMISSION/

SIZE

1521 Characters

FILE INPUTS

Profile

Program /7.0 TRANTEST/ was modified to produce a data file containing the following:

- Time (sec)
- Distance (ft)
- Percent of max. power
- Engine rpm

This data file was used to provide this program with incremental data over the DHEW cycle.

Coefficients

Coefficients for a series of binomials which describe the surfaces of the four emission maps were stored in file /3.0A COEFF/. The coefficients were for Engine A and the four maps were as follows:

- Total weighted emissions
- CO
- HC
- NO_x

PROGRAM FUNCTION

Computes total weighted emissions over the cycle (e.g., DHEW cycle)

PROGRAM OUTPUTS

Summary:

- Total Weighted Emissions (g/std. g)
- Total Carbon Monoxide (g/std-g)
- Total Hydrocarbons (g/std-g)
- Total Oxides of Nitrogen (g/std-g)

Table C-1

PROGRAM – 7.0 TRANTEST

```
100 W=4300
110 F=24
120 D=.5
130 D2=5.75  !DENSITY OF FUEL
140 !PROGRAM /7.0 TRANTEST/   SEPTEMBER 1971
150 REAL A,A1,A2,D1,G,H,H1,H2,H3,I
160 REAL M,M1,M2,N1,P,P1,P2,P3,P4,P5,R1,S,S1,T1,V,V1,S2,V3,W1,W2,W3,W4
170 REAL X1,X2,X3,X4,Y1,Y2
180 INTEGER N
190 STRING Z,Z$,A$
200 Z$="4Z 4-.D 4Z.D 7Z 5-.D 2(4Z.D) 5Z ZZ.3D 3Z.3D 2(3Z.2D)/"
210 PRINT FOR I=1 TO 5
220 PRINT "RUN NO.":
230 INPUT Z
235 A$=Z
236 Z="/7.0 FILE "+Z+"/"
240 OPEN Z,OUTPUT,1
245 PRINT ON 1:"RUN NUMBER-":A$
250 PRINT "TRANS #":
260 INPUT Z
270 Z="/7.0 TRAN "+Z+"/"
280 PRINT ON 1:"TRAN DATA FROM ":Z:"        DATE: ":DATE
290 PRINT ON 1
300 LOAD Z
400 PRINT FOR I=1 TO 2   !THIS MUST BE INST# 400
410 OPEN /PROFILE/,INPUT,2
420 ON ENDFILE(2) GO TO 1030
430 INPUT FROM 2:Z
440 OPEN /7.0 SFC/,RANDOM(6)INPUT,3
450 GOSUB 1200
460 GOSUB 1400
470 PRINT ON 1 FOR I=1 TO 2
480 PRINT ON 1 FOR I=1 TO 2
490 PRINT FOR I=1 TO 3
500 PRINT ON 1:
"TIME ACCEL VELOC  DIST    HP    EFF.   HP   ENG  SFC  -FUEL CONSUMPTI
&:ON-"
510 PRINT ON 1:
"(SEC)(MPH/S)(MPH)  (FT)  (ROAD)  (%)  (ENG)  RPM(#/H-H)(#CUM)(MPGI)(MP
&:GA)"
520 PRINT ON 1:
"____ ____  ___ ___ _  ____ ____ ____ ___ ____ ____ ____ _
&:___"
530 N,P2,S,S1,S3,V,V1=0
1000 INPUT FROM 2:T,A,T1,G
1010 IF A=0 THEN 2000
1020 GO TO 2500
1030 CLOSE 1,2,3
1040 STOP
1200 PRINT ON 1:"WEIGHT...":W:" LBS"
1210 PRINT ON 1:"F.AREA...":F:" SQ FT"
1220 PRINT ON 1:"D.COEF...":D
```

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Table C-1 (Cont.)

```
1230 PRINT ON 1:"FUEL DEN.":D2:" LB/GAL"
1240 PRINT ON 1 FOR I=1 TO 2
1250 PRINT ON 1:Z
1260 PRINT ON 1
1270 RETURN
1400 PRINT
1410 PRINT "WEIGHT...":W:" LBS"
1420 PRINT "F.AREA...":F:" SQ.FT."
1430 PRINT "D.COEF...":D
1440 PRINT "FUEL DEN.":D2:" LB/GAL"
1450 PRINT FOR I=1 TO 3
1460 RETURN
2000 FOR I$=1 TO T    !A=0
2010 N=N+1
2020 GOSUB 3000
2030 NEXT I$
2040 GO TO 1000
2500 FOR I$=1 TO T
2510 N=N+1
2520 GOSUB 3000
2530 NEXT I$
2540 GO TO 1000
3000 V=V+A/2
3010 S2=V/3600  !MILES TRAVELED IN THIS SECOND
3020 A1=A*528/360
3030 V1=V1+A1/2
3040 S=S+V/3600
3050 S1=S1+V1
3060 GOSUB 5000
3070 IF V<=0 THEN 3080 ELSE 3100
3080 H,E1,H2,S3,V,V1=0
3090 GO TO 3170
3100 IF V>50 THEN 3130
3105 IF V>25 THEN 3120
3110 H1=(2790.46-76.5936*V+.810714*V^2)*V1/550
3115 GO TO 3140
3120 H1=(1325.71+14.0429*V-.471429*V^2)*V1/550
3125 GO TO 3140
3130 H1=(652.350+12.285*V-.1675*V^2)*V1/550
3140 P1=MIN(1,ABS(H)/H1)
3150 IF ABS(H)/H1>1 THEN PRINT N:" HP(R) EXCEEDS LIMIT"
3155 IF H<0 THEN 3170
3160 GOSUB 6000 !ENG HP
3170 GOSUB 7000 !RPM
3180 GOSUB 8000   !ACCESSORY AND FW LOSSES
3190 GOSUB 9000 !SFC
3200 V=V+A/2
3210 V1=V1+A1/2
3220  IF N>25 AND V<0 THEN 3230 ELSE 3250
3230 V,V1=0
3240 PRINT IN FORM "/ 'T=' ZZZZ  BB 'V=' SSS.DD /":N,V
3250 GOSUB 4000
```

Table C-1 (Cont.)

```
3260 IF N/100=INT(N/100) THEN PRINT N:
3270 RETURN
4000 !FILE PRINTING ROUTINE
4010 IF V<0 THEN 4020 ELSE 4030
4020 V,V1=0
4030 IF D1<0 THEN PRINT ELSE 4060
4040 PRINT N:" DRAG=":D1
4050 D1=0
4060 IF F2=0 THEN F3=0 ELSE F3=S/F2*D2
4070 IF V=0 THEN 4080 ELSE 4100
4080 PRINT ON 1 IN FORM Z$:
     N,A,V,S1,H,E1*100,H2,N1,S3,F2,0,F3
4090 GO TO 4110
4100 PRINT ON 1 IN FORM Z$:
     N,A,V,S1,H,E1*100,H2,N1,S3,F2,S2/F1*D2,F3
4110 RETURN
5000 D1=1.19*10^-3*D*F*V1^2
5010 R1=W/65*(1+1.4*10^-3*V1+1.2*10^-5*V1^2)+W*G/(SQRT(G^2+100^2))
5020 H=V1/550*(1.1*W*A1/32.1739+D1+R1)
5030 RETURN
6000 !ENG HP ROUTINE (LINKED)
7000 !RPM ROUTINE (LINKED)
8000 !ACCESSORY AND FLYWHEEL LOSSES (LINKED)
9000 !SFC ROUTINE
9005 N1=MAX(N1,800)
9006 IF H<0 THEN 9500
9010 J=INT(N1/200)-3
9020 READ M1 FOR I=1 TO J
9030 READ M2
9040 RESTORE
9050 M=(M2-M1)*(N1-((J+3)*200))/200+M1
9080 P2=H2/M
9090 IF P2>1 THEN P2=1
9100 IF P2<.1 THEN P2=.101
9110 N2=0
9120 FOR I=.1,.2,.3,.4,.5,.55,.6,.65,.7,.75,.8,.85,.9,.95,1
9130 IF I<P2 THEN 9150
9140 GO TO 9160
9150 N2=N2+1,P3=I
9160 NEXT I
9170 INPUT FROM 3 AT (J-1)*15+N2 IN FORM "D.DDDD":X1
9180 INPUT FROM 3 AT (J-1)*15+N2+1 IN FORM "D.DDDD":X2
9190 INPUT FROM 3 AT J*15+N2 IN FORM "Z.DDDD/":X3
9200 INPUT FROM 3 AT J*15+N2+1 IN FORM "Z.DDDD/":X4
9210 IF P3>.45 THEN P4=P3+.05 ELSE P4=P3+.1
9220 P5=(P2-P3)/(P4-P3)
9230 Y1=(X2-X1)*P5+X1
9240 Y2=(X4-X3)*P5+X3
9250 P5=(N1-(J+3)*200)/200
9260 S3=(Y2-Y1)*P5+Y1 !SFC
9270 IF S3<0 THEN PRINT "SFC NEG" ELSE 9290
9280 STOP
```

Table C-1 (Cont.)

```
9290 F1=S3*F2*M/3600 !LBS USED
9300 F2=F2+F1 !CUM LBS"
9310 RETURN
9320 DATA 36.5,47.3,60.5,73,84.9,96.1,106.9,118,129.4,139.2,147.4,
        155,162,168,172
9500 !DECELERATION SFC
9510 S3=5.12727+1.090909E-03*N1*.9
9520 E1,H2=0
9525 F1=S3/3600
9530 GO TO 9300
```

Table C-2

THREE-SPEED TRANSMISSION

```
1 !TRAN 121  (3-SPEED AUTOMATIC)
700 DIM Q(0:15,2)
701 Q(0,1)= .800000E+03
702 Q(0,2)= .000000E+00
703 Q(1,1)= .220500E+03
704 Q(1,2)= .411667E+02
705 Q(2,1)= .168574E+03
706 Q(2,2)= .320147E+02
707 Q(3,1)= .800000E+03
708 Q(3,2)= .000000E+00
709 Q(4,1)= .136170E+03
710 Q(4,2)= .851064E+02
711 Q(5,1)= .364286E+03
712 Q(5,2)= .428571E+02
713 Q(6,1)= .556818E+03
714 Q(6,2)= .227273E+02
715 Q(7,1)= .203431E+03
716 Q(7,2)= .343137E+02
717 Q(8,1)= .800000E+03
718 Q(8,2)= .508475E+02
719 Q(9,1)= .793182E+03
720 Q(9,2)= .318182E+02
721 Q(10,1)= .969767E+03
722 Q(10,2)= .186047E+02
723 Q(11,1)= .153968E+03
724 Q(11,2)= .349206E+02
725 Q(12,1)= .122500E+04
726 Q(12,2)= .325000E+02
727 Q(13,1)= .101429E+04
728 Q(13,2)= .535714E+02
729 Q(14,1)= .119756E+04
730 Q(14,2)= .292683E+02
731 Q(15,1)= .120238E+04
732 Q(15,2)= .190476E+02
735 DIM Q$(6,7)
736 Q$(1,1)=-.149381E+00
737 Q$(2,1)= .106590E+02
738 Q$(3,1)=-.489528E+00
739 Q$(4,1)= .779330E-02
740 Q$(5,1)= .000000E+00
741 Q$(6,1)= .000000E+00
742 Q$(1,2)= .616558E+00
743 Q$(2,2)= .131513E+02
744 Q$(3,2)=-.966406E+00
745 Q$(4,2)= .388168E-01
746 Q$(5,2)=-.673014E-03
747 Q$(6,2)= .000000E+00
748 Q$(1,3)= .413589E+00
749 Q$(2,3)= .162190E+02
750 Q$(3,3)=-.134284E+01
751 Q$(4,3)= .535828E-01
752 Q$(5,3)=-.852284E-03
753 Q$(6,3)= .000000E+00
754 Q$(1,4)= .518534E-01
755 Q$(2,4)= .226111E+02
```

Table C-2 (Cont.)

```
756 Q$(3,4)=-.261546E+01
757 Q$(4,4)= .136373E+00
758 Q$(5,4)=-.260674E-02
759 Q$(6,4)= .000000E+00
760 Q$(1,5)= .477920E-03
761 Q$(2,5)= .403666E+02
762 Q$(3,5)=-.889114E+01
763 Q$(4,5)= .943754E+00
764 Q$(5,5)=-.467433E-01
765 Q$(6,5)= .861255E-03
766 Q$(1,6)= .630868E-03
767 Q$(2,6)= .455041E+02
768 Q$(3,6)=-.109533E+02
769 Q$(4,6)= .121983E+01
770 Q$(5,6)=-.620797E-01
771 Q$(6,6)= .116251E-02
772 Q$(1,7)= .967080E-03
773 Q$(2,7)= .575872E+02
774 Q$(3,7)=-.155893E+02
775 Q$(4,7)= .183167E+01
776 Q$(5,7)=-.957511E-01
777 Q$(6,7)= .161900E-02
6000 !ENG HP
6010 IF V<20 THEN 6230
6020 IF P1<.025 THEN 6200
6030 IF P1<.05 THEN 6160
6040 IF P1<.1 THEN 6120
6050 IF P1<.25 THEN 6080
6060 E1=78+.1*V
6070 GO TO 6500
6080 E(1)=78+.1*V
6090 E(2)=78
6100 E1=(P1-.1)*(E(1)-E(2))/.15+E(2)
6110 GO TO 6500
6120 E(1)=78
6130 E(2)=77.55-.1425*V
6140 E1=(P1-.05)*(E(1)-E(2))/.05+E(2)
6150 GO TO 6500
6160 E(1)=77.55-.1425*V
6170 E(2)=78.5-.425*V
6180 E1=(P1-.025)*(E(1)-E(2))/.025+E(2)
6190 GO TO 6500
6200 E(1)=78.5-.425*V
6210 E1=P1*E(1)/.025
6220 GO TO 6500
6230 !VEL <20 MPH
6240 E(1)=Q$(1,1)+Q$(2,1)*V+Q$(3,1)*V^2+Q$(4,1)*V^3+Q$(5,1)*V^4
       +Q$(6,1)*V^5
6250 E(2)=Q$(1,2)+Q$(2,2)*V+Q$(3,2)*V^2+Q$(4,2)*V^3+Q$(5,2)*V^4
       +Q$(6,2)*V^5
6260 E(3)=Q$(1,3)+Q$(2,3)*V+Q$(3,3)*V^2+Q$(4,3)*V^3+Q$(5,3)*V^4
       +Q$(6,3)*V^5
6270 E(4)=Q$(1,4)+Q$(2,4)*V+Q$(3,4)*V^2+Q$(4,4)*V^3+Q$(5,4)*V^4
       +Q$(6,4)*V^5
6280 E(5)=Q$(1,5)+Q$(2,5)*V+Q$(3,5)*V^2+Q$(4,5)*V^3+Q$(5,5)*V^4
       +Q$(6,5)*V^5
6290 E(6)=Q$(1,6)+Q$(2,6)*V+Q$(3,6)*V^2+Q$(4,6)*V^3+Q$(5,6)*V^4
       +Q$(6,6)*V^5
```

Table C-2 (Cont.)

```
6300 E(7)=Q$(1,7)+Q$(2,7)*V+Q$(3,7)*V^2+Q$(4,7)*V^3+Q$(5,7)*V^4
       +Q$(6,7)*V^5
6310 IF P1<.025 THEN 6490
6320 IF P1<.05 THEN 6470
6330 IF P1<.1 THEN 6450
6340 IF P1<.25 THEN 6430
6350 IF P1<.5 THEN 6410
6360 IF P1<.75 THEN 6390
6370 E1=(P1-.75)*(E(1)-E(2))/.25+E(2)
6380 GO TO 6500
6390 E1=(P1-.5)*(E(2)-E(3))/.25+E(3)
6400 GO TO 6500
6410 E1=(P1-.25)*(E(3)-E(4))/.25+E(4)
6420 GO TO 6500
6430 E1=(P1-.1)*(E(4)-E(5))/.15+E(5)
6440 GO TO 6500
6450 E1=(P1-.05)*(E(5)-E(6))/.05+E(6)
6460 GO TO 6500
6470 E1=(P1-.025)*(E(6)-E(7))/.025+E(7)
6480 GO TO 6500
6490 E1=P1*E(7)/.025
6500 E1=E1/100   !CALCULATE HP
6510 IF H>0 THEN H2=H/E1
6520 RETURN
7000 !ENG RPM
7005 IF V<=0 THEN N1=800 ELSE 7010
7006 RETURN
7010 IF P1<.025 THEN 7810
7020 IF P1<.1 THEN 7560
7030 IF P1<.25 THEN 7290
7040 !50% BAND
7050 IF V<10 THEN 7230
7060 IF V<24 THEN 7180
7070 IF V<44.5 THEN 7130
7080 !50%
7090 I=15
7100 IF V<50 THEN J=10 ELSE J=11
7110 GOSUB 7880
7120 GO TO 7260
7130 !50%
7140 I=14
7150 IF V<28.5 THEN J=9 ELSE J=10
7160 GOSUB 7880
7170 GO TO 7260
7180 !50%
7190 I=13
7200 IF V<17.5 THEN J=8 ELSE J=9
7210 GOSUB 7880
7220 GO TO 7260
7230 !50%
7240 I=12,J=8
7250 GOSUB 7880
7260 N1=(P1-.25)*(E(2)-E(1))/.25+E(1)
7270 GO TO 7920
7280 !END OF 50%
7290 !25% BAND
7300 IF V<17.5 THEN 7470
7310 IF V<28.5 THEN 7430
```

Table C-2 (Cont.)

```
7320 IF V<50 THEN 7370
7330 !25%
7340 I=11,J=7
7350 GOSUB 7880
7360 GO TO 7530
7370 !25%
7380 I=10
7390 IF V<30.5 THEN J=6 ELSE J=7
7400 GOSUB 7880
7410 GO TO 7530
7420 !25%
7430 I=9
7440 IF V<19.5 THEN J=5 ELSE J=6
7450 GOSUB 7880
7460 GO TO 7530
7470 !25%
7480 I=8
7490 J=5
7500 IF V<12.5 THEN J=4
7510 IF V<7.5 THEN J=3
7520 GOSUB 7880
7530 N1=(P1-.1)*(E(2)-E(1))/.15+E(1)
7540 GO TO 7920
7550 !END OF 25% BAND
7560 !10% BAND
7570 IF V<12.5 THEN 7760
7580 IF V<19.5 THEN 7710
7590 IF V<30.5 THEN 7660
7600 !10%
7610 I=7
7620 J=2
7630 GOSUB 7880
7640 GO TO 7790
7650 !10%
7660 I=6
7670 J=2
7680 GOSUB 7880
7690 GO TO 7790
7700 !10%
7710 I=5
7720 IF V<15 THEN J=1 ELSE J=2
7730 GOSUB 7380
7740 GO TO 7790
7750 !10%
7760 IF V<7.5 THEN I=3 ELSE I=4
7770 IF V<8 THEN J=0 ELSE J=1
7780 GOSUB 7880
7790 N1=(P1-.025)*(E(2)-E(1))/.075+E(1)
7800  GO TO 7920
7810 !2.5% BAND
7820 IF V<8 THEN I=0 ELSE 7840
7830 GO TO 7850
7840 IF V<15 THEN I=1 ELSE I=2
7850 GOSUB 7900
7860 N1=P1*E(2)/.025
7870 GO TO 7920
7880 !SUBROUTINE
7890 E(1)=Q(J,1)+Q(J,2)*V
```

Table C-2 (Cont.)

```
7900 E(2)=Q(I,1)+Q(I,2)*V
7910 RETURN
7920 IF N1<800 THEN N1=800
7930 RETURN
8000 !ACCESSORY AND FLYWHEEL LOSSES
8010 ! NO AIR CONDITIONING
8020 H2=H2+(10.9199E-07*N1^18.8149E-01)*N1/5252  !ENGINE FAN
8030 IF N1<2200 THEN 8040 ELSE 8060
8040 H2=H2+(-12.322974+6.6444128E-02*N1-7.0475694E-05*N1^2+
     3.2954301E-08*N1^3-7.1021053E-12*N1^4+5.6619139E-16*N1^5)*N1/5252
    !GENERATOR  <2200 RPM
8050 GO TO 8070
8060 H2=H2+(1/(.038335+.000053*N1))*N1/5252  !GENERATOR >2200 RPM
8070 N3=4800*(24*(1-(V/85)^2)+1)^.5   !FW RPM
8080 ! NO FLYWHEEL LOSS
8090 H2=H2+3.1*N1/5252   !POWER STEERING LOSS
8100 RETURN
GO TO 400
```

Appendix D

FLYWHEEL KINETIC ENERGY DISTRIBUTION AFTER BURST

This appendix presents an analysis indicating the relationship of energy distribution after burst to the number of resulting flywheel pieces. The flywheel is assumed to break into N equal-size sectors, the centers of gravity of which are at radius $\bar{r}$.

$$\bar{r} = \frac{2N \sin(\pi/N)}{3\pi} \left(\frac{R_o^3 - R_i^3}{R_o^2 - R_i^2} \right)$$

$$I_{CG} = \frac{\rho \, t \, N}{18 \, \pi \, g} \left[\frac{9\pi^2}{N^2} \left(R_o^4 - R_i^4 \right) - 8 \sin^2 (\pi/N) \frac{\left(R_o^3 - R_i^3 \right)^2}{R_o^2 - R_i^2} \right]$$

Total kinetic energy $KE = N \left(0.5 \, mv^2 + 0.5 \, I_{CG} \, \omega^2 \right)$

$$m = \frac{\pi \rho t}{N g} \left(R_o^2 - R_i^2 \right)$$

$$v = \omega F = \frac{2N\omega}{3\pi} \sin(\pi/N) \left(\frac{R_o^3 - R_i^3}{R_o^2 - R_i^2} \right)$$

Translational kinetic energy:

$$N \left(0.5 \, mv^2 \right) = \frac{4N^2 \rho \, t \, \omega^2}{18 \, \pi \, g} \left[\sin^2 (\pi/N) \right] \frac{\left(R_o^3 - R_i^3 \right)}{R_o^2 - R_i^2}$$

Rotational kinetic energy:

$$N\left(0.5 I_{CG}\,\omega^2\right) = \frac{N^2 \rho t \omega^2}{18\,\pi\, g}\left[(9\,\pi^2/2\,N^2)\left(R_o^4 - R_i^4\right) - 4\sin^2(\pi/N)\,\frac{\left(R_o^3 - R_i^3\right)^2}{R_o^2 - R_i^2}\right]$$

$$KE_{Total} = KE_{Transl} + KE_{Rotation} = \frac{\pi \rho t \omega^2}{4g}\left(R_o^4 - R_i^4\right)$$

Figure D-1 shows the distribution of kinetic energy versus the number of burst fragments, assuming them to be equal sectorial pieces.

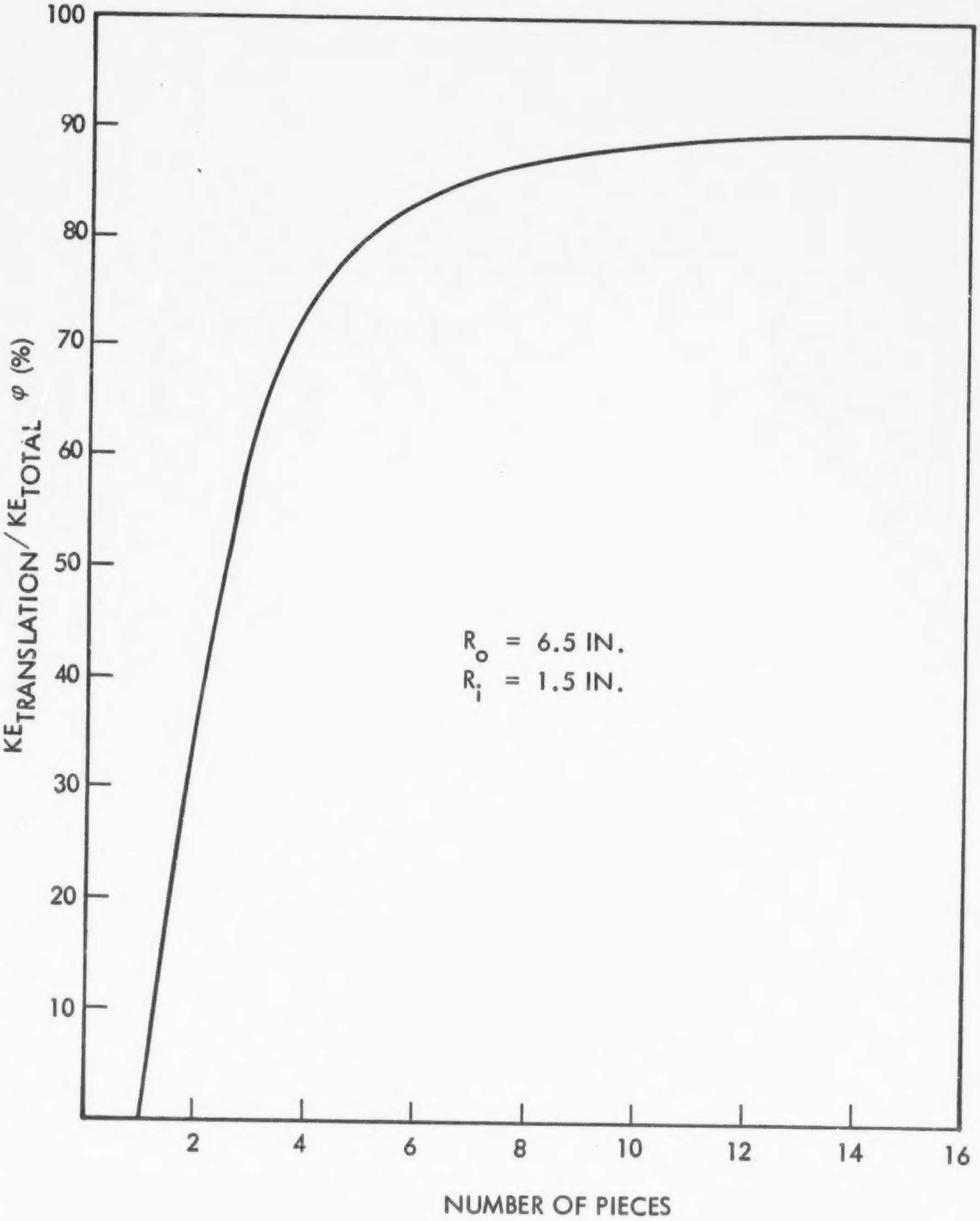


Fig. D-1 Flywheel Burst Energy Distribution

Appendix E
CONTAINMENT RING DESIGN

This appendix describes two methods employed in the Flywheel Drive Systems Study effort for the design of containment rings.

Method 1

This method is based on the assumption of uniform stress F/A over a cross section of the containment ring.

$$F = \text{centrifugal force over a radial section of the flywheel}$$

$$= \frac{\rho t \omega^2}{3g} \left(R_o^3 - R_i^3\right)$$

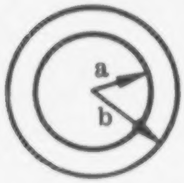
where

ρ = flywheel density = 0.283 lb/in.^{3}
t = flywheel thickness = 3.5 in.
ω = flywheel angular velocity = 2,513 rad/sec (24,000 rpm)
R_o = flywheel outer radius = 6.5 in.
R_i = flywheel inner radius = 1.5 in.

Then

$$F = 1,465,000 \text{ lb}$$

a. Ring Material: SAE-4340 steel, $F_{t_u} = 250,000$ psi



Ring axial length = 3.5 in.
Cross-section area = A
Inside radius a = 6.5 in.

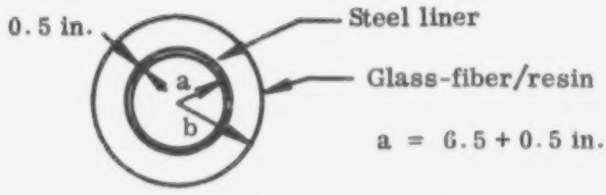
Assume $\sigma_t = F/A = 200,000$ psi

$$A = \frac{1,465,000}{200,000} = 7.32 \text{ in.}^2$$

Radial thickness = 7.32/3.5 = 2.09 in.

Outside radius b = 6.5 + 2.09 = 8.59 in.

b. Ring Material: "E" glass-filament/resin wound on steel liner


0.5 in.
Steel liner
Glass-fiber/resin
a
b

a = 6.5 + 0.5 in. = 7 in.

Assume F/A = 155,000 psi

$$A = \frac{1,465,000}{155,000} = 9.44 \text{ in.}^2$$

$$\text{Radial thickness} = 9.44/3.5 = 2.70 \text{ in.}$$

$$\text{Outside radius } b = 7 + 2.7 = 9.7 \text{ in.}$$

Method 2

This method is based on the assumption of uniform internal pressure P_i acting over the inside diameter of the containment ring.

For a thick-walled pressure vessel, the tangential and radial stresses in the walls are, respectively:

$$\sigma_t = \frac{a^2 P_i}{b^2 - a^2}\left(1 + \frac{b^2}{r^2}\right)$$

$$\sigma_r = \frac{a^2 P_i}{b^2 - a^2}\left(1 - \frac{b^2}{r^2}\right)$$

where

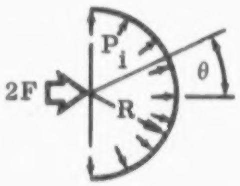
a = inside radius
b = outside radius

The maximum tangential stress occurs at the inside radius, $r = a$:

$$\text{Maximum } \sigma_t = P_i\left(\frac{b^2 + a^2}{b^2 - a^2}\right)$$

The pressure P_i is found from the flywheel force F of Method 1. The radius of the flywheel is assumed equal to the inside radius of the ring so that contact occurs over the entire semicircular periphery. Thus:

$$2F = \int_{-\pi/2}^{\pi/2} P_i \, t \cos\theta \, (R \, d\theta)$$



$$= 2 \, t \, R \, P_i$$

$$P_i = F \, (t R)$$

$$P_i = \frac{\rho \omega^2}{3g} \left(\frac{R_o^3 - R_i^3}{R_o} \right)$$

$$= 64,354 \text{ psi}$$

Then

$$\text{Maximum } \sigma_t = 64,354 \left(\frac{b^2 + a^2}{b^2 - a^2} \right)$$

a. Ring Material: SAE-4340 steel, $F_{t_u} = 250,000$ psi

Assume $\sigma_{t_{max}} = 200,000$ psi

$$a = 6.40 \text{ in.}$$

$$\frac{b^2 + 42.25}{b^2 - 42.25} = \frac{200,000}{64,354} = 3.11$$

$$b^2 = \frac{4.11\ (42.25)}{2.11} = 82.3$$

$$b = 9.07 \text{ in.}$$

$$\text{Radial thickness} = 9.07 - 6.50 = 2.57 \text{ in.}$$

b. Ring Material: "E" glass-filament/resin wound on steel liner

$$a = 6.5 + 0.5 = 7 \text{ in.}$$

$$\text{Assume } \sigma_{t_{max}} = 155,000 \text{ psi}$$

$$\frac{b^2 + 49.0}{b^2 - 49.0} = \frac{155,000}{64,354} = 2.41$$

$$b^2 = \frac{3.41\ (49)}{1.41} = 118.5$$

$$b = 10.89 \text{ in.}$$

$$\text{Radial thickness} = 10.89 - 7 = 3.89 \text{ in.}$$

Detailed design calculations are presented for ring C, which is a solid steel ring of rectangular cross section.

Ring Material: SAE-4340, $F_{t_u} = 150,000$ psi

1. Desired energy of flywheel at burst = 0.9 hp-hr

This corresponds to a burst speed of

$$\omega^2 = \frac{33,000\,(12)\,(60)\,(2)\,(KE)}{I}$$

$$= 4.752 \times 10^7 \left(\frac{0.90}{7.17}\right) = 5,964,000$$

$$\omega = 2,440 \text{ rad/sec } (23,300 \text{ rpm})$$

Flywheel $F_{t_u} = 125,000$ psi

Assume $\sigma_{abs} = F_{t_y} = 103,000$ psi

$$\sigma_{abs} = 103,000 = \frac{\rho\omega^2}{3g}\left(\frac{R_o^3 - R_i^3}{R_o - R_i - a}\right)$$

$$= 0.0662663\left(\frac{\omega^2}{5 - a}\right)$$

$$5 - a = \frac{0.0662663\,(2,440)^2}{103,000}$$

$$= 3.83$$

Notch length $\ell = 5.0 - 3.8 = 1.2$ in.

2. Allow 0.08 in. static radial clearance

   Ring inside radius = 6.50 + 0.08 = 6.58 in.

3. For a burst speed of 23,300 rpm, the equivalent internal pressure P_i on the ring is

$$P_i = \frac{\rho\omega^2}{3g}\left(\frac{R_o^3 - R_i^3}{R_o}\right)$$

$$= 60,717 \text{ psi}$$

Maximum tangential stress in the ring,

$$\sigma_{t_{max}} = P_i \left(\frac{b^2 + a^2}{b^2 - a^2} \right)$$

$$= 60,717 \left(\frac{b^2 + \overline{6.58}^2}{b^2 - \overline{6.58}^2} \right)$$

Letting $\sigma_{t_{max}} = F_{t_u} = 150,000$ psi

$$\frac{b^2 + 43.3}{b^2 - 43.3} = \frac{150,000}{60,717} = 2.47$$

$$b^2 = \frac{3.47\,(43.3)}{1.47} = 102.21$$

Ring outside radius b = 10.11 in.

Ring radial thickness = 10.11 - 6.58 = 3.53 in.

Actual ring outside diameter = 20.30 in.

Ring weight = (0.283) (3.5) (3.60) (2π) (6.58 + 1.80)

= 187.75 lb

Appendix F

FLYWHEEL CONTAINMENT TESTS

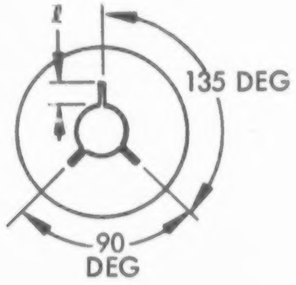
All flywheel containment tests utilized a flywheel with the following characteristics:

• Material	Steel (SAE-4130 or SAE-4340)
• Outside Diameter	13 in.
• Inside Diameter	3 in.
• Thickness	3.5 in.
• Weight	125 lb

Burst speed was controlled by cutting radial notches in the bore to a depth ℓ, determined from the equation:

$$\sigma_{abs} = \frac{\rho\omega^2}{3g} \frac{R_o^3 - R_i^3}{R_o - R_i - \ell}$$

The following sketch shows the location of the notches:



Moment of inertia:

$$I_p = \frac{\pi\rho t}{2g} \quad R_o^4 - R_i^4 \quad = 7.17/\text{in.-lb-sec}^2$$

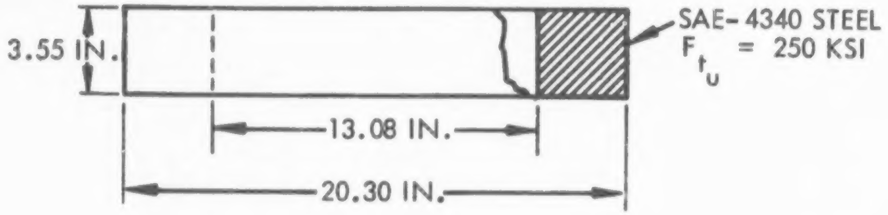
Kinetic energy at 24,000 rpm (2,513 rad/sec):

$$KE = (I\omega^2)/2 = 22.64 \times 10^6 \text{ in.-lb}$$
$$= 0.95 \text{ hp-hr}$$

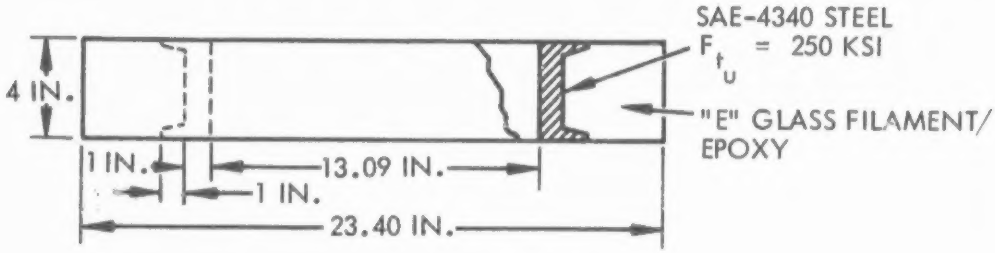
Figure F-1 shows the types of containment ring utilized in the flywheel containment tests, and Table F-2 presents a chronology of the test program.

TYPE

A


3.55 IN.
13.08 IN.
20.30 IN.
SAE-4340 STEEL
F_{t_u} = 250 KSI

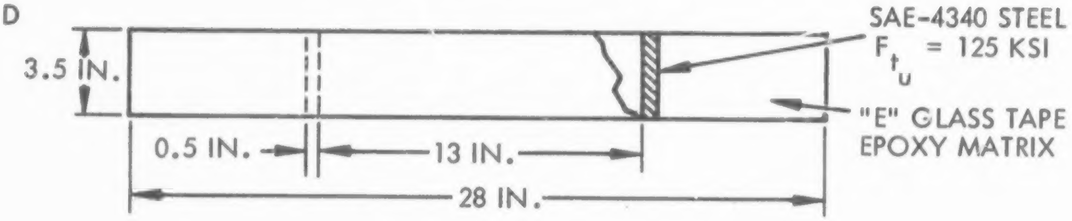
B


4 IN.
1 IN.
13.09 IN.
1 IN.
23.40 IN.
SAE-4340 STEEL
F_{t_u} = 250 KSI
"E" GLASS FILAMENT/ EPOXY

C

SAME AS TYPE A EXCEPT F_{t_u} = 150 KSI

D


3.5 IN.
0.5 IN.
13 IN.
28 IN.
SAE-4340 STEEL
F_{t_u} = 125 KSI
"E" GLASS TAPE EPOXY MATRIX

E

SAME AS TYPE D EXCEPT WITHOUT MATRIX; TAPE WIDTH 3 IN.

F

SAME AS TYPE D EXCEPT WITH POLYESTER MATRIX; TAPE WIDTH 4 IN.

Fig. F-1 Types of Containment Ring Used in Flywheel Containment Tests

Table F-1

SUMMARY OF CONTAINMENT TESTS

Test Date	Flywheel		Notch Depth (in.)	Containment Ring Type(a)	Radial Gap (in.)	Maximum Speed (rpm)	Kinetic Energy (hp-hr)	Remarks
	Material	U. T. S. (psi)						
11-5-71	4130	Normalized	0.08	A	0.040	20,420	0.69	Momentum transfer No burst
11-12-71	4130	Normalized	0.08	B	0.075	23,840	0.94	Momentum transfer No burst
11-23-71	4340	125,000	0.08	B	0.100	31,900	1.68	Exceeded design limits of ring. Test terminated
11-24-71	4340	125,000	1.6	B	0.115	19,540	0.63	Flywheel burst Ring held
12-8-71	4340	125,000	1.2	C	0.078	22,820	0.86	Flywheel burst Ring held
12-17-71	4340	125,000	1.2	D	0.078	24,310	0.98	Flywheel burst Ring failed
1-5-72	4340	125,000	1.2	E	0.078	24,525	0.99	Flywheel burst Ring failed
1-14-72	4340	125,000	2.9	F	0.063	16,750	0.46	Flywheel burst Ring held

(a) See p. F-3.

Table F-2

CHRONOLOGY – FLYWHEEL CONTAINMENT TESTS

Date	Test Conditions and Results
Oct 18, 1971	Flywheel: SAE-4130; normalized; notch depth, 0.08 in.; ring type A; radial gap 0.044 in. Test configuration included small support bearing on drive spindle approximately 1 in. above flywheel Could not exceed 5,700 rpm because of flywheel "chattering" around inside of ring
Oct 21, 1971	Same conditions as test of 18 Oct 1971 Could not exceed 5,000 rpm due to chattering of flywheel in ring
Oct 25, 1971	Same conditions as test of 21 Oct 1971; radial gap increased to 0.083 in. Chattering prevented exceeding speed of 4,600 rpm
Nov 2, 1971	Same conditions as test of 25 Oct 1971; new flywheel, hub, and spindle machined as a unit to maintain concentricity Chattering prevented exceeding speed of 4,600 rpm
Nov 2 to 4, 1971	Designed and fabricated bearing and support assembly to locate lower surface of flywheel and fix axis of rotation; retained original bearing on spindle above flywheel
Nov 5, 1971	Same conditions as test of 2 Nov 1971; radial gap, 0.040 in. Flywheel seized ring at 20,420 rpm, effecting momentum transfer, spindle sheared; ring and flywheel intact
Nov 12, 1971	Flywheel: SAE-4130, normalized; notch depth, 0.08 in.; ring type B. Same upper and lower support bearings as test of 5 Nov 1971; radial gap, 0.075 in. Flywheel seized ring at 23,840 rpm, effecting momentum transfer, spindle sheared; flywheel and ring intact
Nov 16, 1971	Flywheel: SAE-4340; 125 ksi; notch depth, 0.08 in.; ring type B; radial gap, 0.100 in.; same bearing configuration as test of 5 Nov 1971 Spindle broke at 15,700 rpm; no evidence of flywheel in contact with ring
Nov 19, 1971	Same conditions as previous test of 16 Nov 1971; radial gap, 0.115 in. Spindle broke at 12,600 rpm; no evidence of flywheel in contact with ring
Nov 23, 1971	Same flywheel and ring as test of 19 Nov 1971; upper and lower bearings removed, leaving spindle supported only by turbine rotor; radial gap, 0.100 in. Flywheel attained 31,900 rpm without difficulty; air shut off to avoid damage to test equipment
Nov 24, 1971	Flywheel: SAE-4340, 125 ksi; notch depth, 1.6 in.; ring type B; radial gap, 0.115 in. Same bearing configuration as test of 23 Nov 1971 Flywheel burst at 19,540 rpm; ring failed; turbine damaged by shock
Nov 25 to Dec 7, 1971	Turbine lower housing replaced; turbine reassembled and run in
Dec 8, 1971	Flywheel: SAE-4340, 125 ksi; notch depth, 1.2 in.; ring type C; radial gap, 0.078 in. Flywheel burst at 22,820 rpm; ring held, turbine damaged by shock
Dec 9 to 15, 1971	Turbine drive bushing and lower housing replaced. Turbine reassembled and run in
Dec 17, 1971	Flywheel: SAE-4340, 125 ksi; notch depth, 1.2 in.; ring type D; radial gap, 0.078 in. Additional 4-in. steel plate added to spin pit to increase volume of cavity Flywheel burst at 24,3[illegible] rpm, ring failed
Jan 4, 1972	Flywheel: SAE-4340, 125 ksi; notch depth, 1.2 in., ring type E; radial gap, 0.078 in. Air shut off at 4,500 rpm because of excessive vibration in the pit structure
Jan 5, 1972	Same conditions as test of 4 Jan 1972; flywheel rebalanced Flywheel burst at 24,525 rpm; ring failed
Jan 14, 1972	Flywheel: SAE-4340, 125 ksi notch depth, 2.9 in., ring type F; radial gap, 0.063 in. Flywheel burst at 16,750 rpm; ring held; turbine damaged by shock

Appendix G

CALCULATIONS FOR MOUNTING THE FLYWHEEL/SHAFT

The more pertinent calculations used in determining the flywheel/shaft mounting arrangement and other needs relative to the bearings, seals, and vacuum pumps are presented in this appendix.

The following equations are oil jet calculations used to determine flow and power requirements for oil flow through a 0.030 orifice:

$$q = CA\sqrt{2g\,h_L} = CA\sqrt{\frac{2g\,(144)}{\rho}} \times \sqrt{\Delta P}$$ per Crane Technical Paper no. 410

where

C = flow coefficient for nozzle

$$\frac{d_o}{d_I} = \frac{0.030 \text{ orifice dia.}}{0.180 \text{ pipe ID}} = 0.167$$

C = 985 for nozzle

C = 0.6 for square-edged orifice

$$A = \text{area of orifice} = \frac{(0.030)^2}{4}$$

$$= 0.000785 = 78.5 \times 10^5 \text{ in.}^2$$

$$= 0.545 \times 10^{-5} \text{ ft}^2$$

Assume

ΔP = 25 psi, 40, 60, and 80

$\sqrt{\Delta P}$ = 5, 6.32, 7.74 and 8.94

$$\rho = \text{lb/ft}^3 \text{ of oil} = 0.02963 \text{ lb/ft}^3 \text{ (petroleum oils)}$$

$$q = (0.6)(5.45)(10^{-6})\sqrt{\frac{2 \times 32.2\ (144)}{0.02963}} \times \sqrt{\Delta P}$$

$$q = 1.82 \times 10^{-3}\sqrt{\Delta P}$$

Lube Oil Pressure	Disc Pressure	P	ft^3/sec	gpm	hp
25 + atm	atm	25	0.009	0.067	0.00098
40 + atm	atm	40	0.015	0.086	0.00200
60 + atm	atm	60	0.141	0.105	0.00367
80 + atm	atm	80	0.163	0.122	0.00568

Assume 1 jet of oil. Minimum number of jets should be 2 per bearing, 3 preferred.

Pressure (psi)	hp	
	4 Jets	6 Jets
25	0.00392	0.00588
40	0.00800	0.01200
60	0.01470	0.02200
80	0.0270	0.03410

Using 4 jets (2 per bearing) as minimum and 40 psia oil pressure:

$$\text{Flow} = 0.086 \times 4 = 0.344 \text{ gpm}$$

$$\text{hp} = \frac{0.344 \times 40}{1714 \times 0.85} = 0.008 \text{ hp}$$

Centrifugal Force due to flywheel rotation:

cg Displacement = 0.0002 in.

$$CF = 3.41 \times 10^{-4}\ W/R\ N^2$$

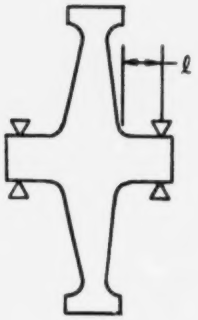
where

W = weight (lb)
R = displacement (ft)
N = speed (rpm)

Speed (rpm)	Centrifugal Force (psi)			
	Baseline	1	2	3
	86 lb	160 lb	86 lb	42 lb
28,000	384	714	384	186
24,000	282	440	282	115
20,000	196	363	196	95
16,000	125	232	125	61
12,000	71	131	72	34
8,000	31	58	31	15

Critical Speed Analysis:

Baseline Flywheel



Data

6 in. centers between bearings
Shaft, 30 mm = 1.18 dia.
$I = 9.45 \times 10^{-2}$
Flywheel weight = 86 lb
$\ell = 1.5$ in. (cantilevered section of shaft)

$$k = \frac{3EI}{\ell^3} = \frac{3 \times 30 \times 10^6 \times 9.45 \times 10^{-2}}{(1.5)^3}$$

$$= 25 \times 10^5 \text{ lb/in.}$$

Total spring rate, shaft on both sides acting as springs:

$$k_\tau = 50 \times 10^5 \text{ lb/in.}$$

$$\omega n = \sqrt{\frac{k_\tau}{M}} = \sqrt{\frac{50 \times 10^5}{86/386}}$$

$$= 4730 \text{ rad/sec}$$

$$= 4730 \times \frac{60}{2k} = 45{,}100 \text{ cpm}$$

This exceeds nominal operating speeds by 187%.

Table G-1

WINDAGE LOSS, COMPUTER RUN BASELINE FLYWHEEL DESIGN

R(0) = 6.53 Flywheel radius (in.)
T = 3.5 Tip thickness (in.)
N = 24000 Speed (rpm)
T = 519.4 Temperature (°R)
U = 4.31E-02 Air Viscosity (lb/hr-ft)

mm Hg	psi	hp Loss
0	0	0
1	1.9342105E-02	.13301009
2	3.8684211E-02	.23158402
3	5.8026316E-02	.32031819
4	7.7368421E-02	.4032112
5	9.6710526E-02	.48201505
6	.11605263	.55770636
7	.13539474	.63090363
8	.15473684	.70203148
9	.17407895	.77139817
10	.19342105	.83923695
11	.21276316	.90572998
12	.23210526	.97102317
13	.25144737	1.0352358
14	.27078947	1.098467
15	.29013158	1.1608005
16	.30947368	1.2223078
17	.32881579	1.2830504
18	.34815789	1.3430822
19	.3675	1.4024503
20	.38684211	1.4611964
21	.40618421	1.5193577
22	.42552632	1.5769675
23	.44486842	1.6340557
24	.46421053	1.6906495
25	.48355263	1.7467735
26	.50289474	1.8024502
27	.52223684	1.8577001
28	.54157895	1.9125422
29	.56092105	1.9669938
30	.58026316	2.0210711

Table G-2

WINDAGE LOSS, COMPUTER RUN
FLYWHEEL NO. 2 (PRELIMINARY)

R(0) = 6.53 Flywheel Tip radius (in.)
T = 3.5 Tip thickness (in.)
N = 24000 Speed (rpm)
T = 519.4 Temperature (°R)
U = 4.31E-02 Air Viscosity (lb/hr-ft)

mm Hg	psi	hp Loss
0	0	0
1	1.9342105E-02	.13301009
2	3.8684211E-02	.23158402
3	5.8026316E-02	.32031819
4	7.7368421E-02	.4032112
5	9.6710526E-02	.48201505
6	.11605263	.55770636
7	.13539474	.63090363
8	.15473684	.70203148
9	.17407895	.77139817
10	.19342105	.83923695
11	.21276316	.90572998
12	.23210526	.97102317
13	.25144737	1.0352358
14	.27078947	1.098467
15	.29013158	1.1608005
16	.30947368	1.2223078
17	.32881579	1.2830504
18	.34815789	1.3430822
19	.3675	1.4024503
20	.38684211	1.4611964
21	.40618421	1.5193577
22	.42552632	1.5769675
23	.44486842	1.6340557
24	.46421053	1.6906495
25	.48355263	1.7467735
26	.50289474	1.8024502
27	.52223684	1.8577001
28	.54157895	1.9125422
29	.56092105	1.9669938
30	.58026316	2.0210711

Table G-3

WINDAGE LOSS COMPUTER RUN
FLYWHEEL NO. 1 (PRELIMINARY)

R(0) = 5 Tip Radius (in.)
T = 7 Tip Thickness (in.)
N = 24000 Speed (rpm)
T = 519.4 Temperature (°R)
U = 4.31E-02 Air Viscosity (lb/hr-ft)

```
mm Hg         psi                      hp Loss
  0      0       0
  1      1.9342105E-02             7.3623098E-02
  2      3.8684211E-02             .12818526
  3      5.8026316E-02             .17730096
  4      7.7368421E-02             .2231835
  5      9.6710526E-02             .26680262
  6      .11605263      .30869891
  7      .13539474      .3492147
  8      .15473684      .38858504
  9      .17407895      .42698055
 10      .19342105      .46453035
 11      .21276316      .50133525
 12      .23210526      .53747601
 13      .25144737      .57301867
 14      .27078947      .60801811
 15      .29013158      .64252066
 16      .30947368      .67656585
 17      .32881579      .71018783
 18      .34815789      .74341632
 19      .3675      .77627745
 20      .38684211      .80879431
 21      .40618421      .84098747
 22      .42552632      .87287536
 23      .44486842      .90447456
 24      .46421053      .93580009
 25      .48355263      .96686557
 26      .50289474      .99768345
 27      .52223684      1.0282651
 28      .54157895      1.058621
 29      .56092105      1.0887608
 30      .58026316      1.1186934
```

Table G-4

WINDAGE LOSS COMPUTER RUN
FLYWHEEL NO. 3

R(0) = 10.22 Tip Radius (in.)
T = 1 Tip Thickness (in.)
N = 24000 Speed (rpm)
T = 519.4 Temperature (°R)
U = 4.31E-02 Air Viscosity (lb/hr-ft)

```
mm Hg       psi                  hp Loss

  0      0       0
  1      1.9342105E-02       .57288463
  2      3.8684211E-02       .99745008
  3      5.8026316E-02       1.3796349
  4      7.7368421E-02       1.7366615
  5      9.6710526E-02       2.0760757
  6      .11605263      2.4020839
  7      .13539474      2.7173502
  8      .15473684      3.0237032
  9      .17407895      3.3224709
 10      .19342105      3.6146577
 11      .21276316      3.9010482
 12      .23210526      4.182271
 13      .25144737      4.4588396
 14      .27078947      4.7311814
 15      .29013158      4.9996566
 16      .30947368      5.2645731
 17      .32881579      5.5261963
 18      .34815789      5.7847578
 19      .3675     6.0404606
 20      .38684211      6.2934845
 21      .40618421      6.5439897
 22      .42552632      6.7921195
 23      .44486842      7.0380029
 24      .46421053      7.2817567
 25      .48355263      7.5234871
 26      .50289474      7.7632907
 27      .52223684      8.0012563
 28      .54157895      8.2374653
 29      .56092105      8.4719927
 30      .58026316      8.7049078
```

Appendix H

FLYWHEEL SUPPORT BEARINGS ANALYSIS

An analysis of the bearings that support the flywheel shaft is given in this appendix. Included are calculations for determination of bearing speed limits, life, and drag torques.

SPEED LIMIT ESTIMATES USING DN LIMITS AND TAC LIMITS FOR 30-MM-BORE BEARINGS

$$\text{TAC} = \frac{D' N^3 d^3}{\cos^3 B}$$

where

D = bearing bore, (mm)
D' = bearing pitch diameter, (mm)
N = speed (rps)
d = ball diameter (in.)
B = initial contact angle (deg) = 12

Bearing No.	O.D. (mm)	I.D. (mm)	D' (mm)	d (in.)	d^3 (in.^{3})	$D' d^3$ (mm in.^{3})
1096	47	30	38.5	0.2031	0.0084	0.322
106	55	30	42.5	0.2813	0.0222	0.9435
206	62	30	46.0	0.3125	0.0305	1.4030
306	72	30	51.0	0.4375	0.0834	4.2534
406	90	30	60.0	0.6875	0.3250	19.5000

When TAC = 31×10^8

$$N^3 = \frac{TAC \cos^3 B}{D' d^3} = \frac{29 \times 10^8}{D' d^3}$$

N^3	N (rps)	N (rpm)
9.0×10^9	2080	124,000
3.07×10^9	1453	87,200
2.06×10^9	1313	78,700
0.68×10^9	880	52,700
0.149×10^9	530	31,800

When TAC = 7×10^8

$$N^3 = \frac{6.55 \times 10^8}{D' d^3} \quad :$$

N^3	N (rps)	N (rpm)
2.035×10^9	1260	75,600
0.695×10^9	886	53,000
0.467×10^9	776	46,500
0.154×10^9	536	32,000
0.034×10^9	323	19,400

Speed N when $D' N = 1 \times 10^6$ and $D' N = 1.5 \times 10^6$:

N When $D' N = 1 \times 10^6$	N When $D' N = 1.5 \times 10^6$
26,000	39,000
24,000	37,000
21,700	32,500
19,600	29,400
16,680	25,000

BASELINE FLYWHEEL ASSEMBLY BEARING LIFE ANALYSIS

The life expectancy of a ball bearing for 90 percent reliability is called an L_{10} rating. The L_{10} rating for the 206K bearing is calculated as follows:

$$L_{10} = \frac{50,000}{N} \; \frac{\left(C_B\right)^3}{R_E}$$

where

N = rpm
C_B = basic radial load rating at 33-1/3 rpm
R_E = equivalent radial load
L_{10} = life (hr)

The equivalent L_{10} life of a bearing subject to varying speeds for varying times can be determined by the formula

$$L = \frac{1}{\frac{P_1}{L_1} + \frac{P_2}{L_2} \; . \; . \; . + \frac{P_N}{L_N}}$$

where

L = equivalent hours of L_{10} life
P_1 = portions of time expressed as a decimal fraction of time that load and speed are in effect
L_1 = calculated life of each bearing at each load and speed

The L_{10} calculations are tabulated below.

Percent of Time	Normal Loading, Radial	Gyro-Induced Loads	Total Loads, Radial	Operating Speed	Theoretical Life L_{10} (hr)
2.5	282	600	882	24,000	138
2.5	282		282	24,000	4210
2.5	237	300	537	22,000	667
2.5	237		237	22,000	7768.75
17	196	200	396	20,000	1831
8	196		196	20,000	15,106
35	159	100	259	18,000	7248
20	96	40	136	14,000	64,591
10	70.5	–	70.5	12,000	540,946
10	31	–	31	8,000	9.5×10^6

Combined L_{10} bearing life for complete duty cycle: 3154 hr.

TYPICAL CALCULATIONS FOR DETERMINING BEARING DRAG LOSSES

Brg 206 (30 × 62 × 15), α = 12 deg, speed = 8000 rpm

Friction Torque:

$$0.083\, f_1 P_B d_m + 1.183 \times 10^{-6} f_o (\gamma N)^{2/3} d_m^3$$

where

$$f_1 = z \left[\frac{P_c}{C_o}\right]^{\gamma}$$

$$= 0.00094\,(0.138)^{0.46} = 0.00011$$

P_B = 31 $\qquad\gamma$ = 28 cts

d_m = 1.811 $\qquad N$ = 8,000

d_m^3 = 5.94 $\qquad(\gamma N)^{2/3}$ = 1,280

$$T = (0.083)\,(1.17 \times 10^{-4})\,(31)\,(1.811) + (1.183 \times 10^{6})\,(1280)\,(5.94) = 0.00956 \text{ in.-lb}$$

$$hp = \frac{(0.00956)\,(8000)}{63{,}000} = 0.00122 \text{ hp/brg}$$

Speed (rpm)	Horsepower Loss (hp/brg)
8,000	0.0012
12,000	0.0068
16,000	0.012
20,000	0.018
24,000	0.025
28,000	0.036

Appendix I

SEAL LEAKAGE CALCULATIONS

Seal leakage calculations are presented in this appendix.

LABYRINTH SEALS

Preliminary gas flow loss estimates, based on steam turbine work:

$$W = 25\ KA \sqrt{\frac{P_1}{V_1} \left[1 - \left(\frac{P_2}{P_1}\right)^2\right] \Big/ \left[N - \ln \frac{P_2}{P_1}\right]}$$

W = flow (lb/hr)

K = coefficient (experimental)

= 50 for interlocking labyrinth; varies from 100 to 60 for noninterlocking seals, based on radial clearance to spacing ratio of 5 to 50; uses 100 noninterlocking short spacings

For 0.001-rad clearance,

A = area = $\pi d\ (0.001)\ \text{in.}^2$

P_1 = initial pressure = 14.7 psia

V_1 = initial specific volume = 13.28 ft^3/lb

P_2 = final pressure = 5 mm = 0.097 psia

N = number of throttlings; assume 3 per side

$$W = 25\ (100)\ A \sqrt{\frac{\frac{14.7}{13.27} \left[1 - \left(\frac{0.097}{14.7}\right)^2\right]}{\left[6 - \ln \frac{0.097}{14.7}\right]}}$$

$W = A\ (2.67 \times 10^3)$ lb/hr

For 1.5d:

$$W = (4.71 \times 10^{-3})(2.67 \times 10^{3}) = 12.6 \text{ lb/hr} = 0.0035 \text{ lb/sec (278 CFM)}$$

For 2.0d:

$$W = (6.29 \times 10^{-3})(2.67 \times 10^{3}) = 16.8 \text{ lb/hr} = 0.0047 \text{ lb/sec (374 CFM)}$$

With larger radial clearances:

Clearance	Loss 1.5-in. Diameter		Loss 2.0-in. Diameter	
	lb/sec	CFM	lb/sec	CFM
0.001	0.0035	278	0.0047	374
0.003	0.0105	835	0.0141	1120
0.006	0.0210	1670	0.0282	2240
0.009	0.0315	2500	0.0423	3380

Appendix J
FACE SEAL TEST REPORT

The test results of the high-speed rotary face seal tests are presented in this Appendix.

The test objective was to determine the friction drag torque and vacuum sealing ability of a face-type shaft seal at high rotary speeds for use on high-speed flywheel applications. The test setup for this test is shown by Fig. J-1 (seal test setup), Fig. J-2 (drawing of seal arrangement), and Fig. J-3 (details of seal).

TEST PROCEDURE

The seal was tested with three different nose loadings at the following revolutions per minute:

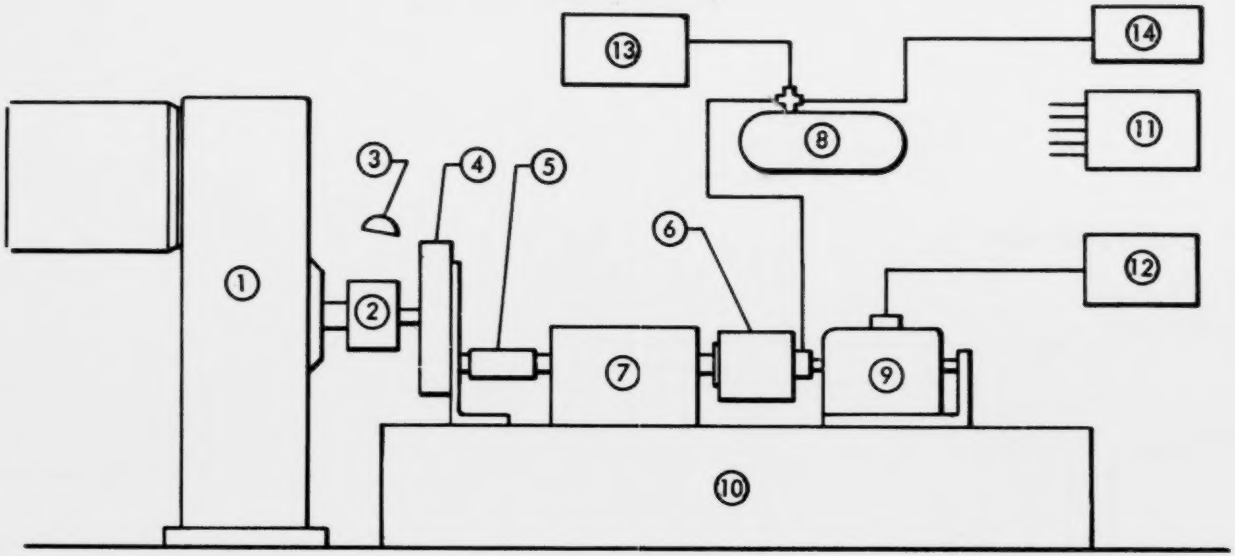
6,000
8,000
12,000
16,000
20,000

The first test was run to determine drag torque values with a maximum of 5.0 mm Hg air pressure in the seal cavity. The second test was run to determine vacuum leakage rate at speeds noted.

TEST RESULTS

Test results are shown in Tables J-1 and J-2 and the drag torque and horsepower curve is shown in Fig. J-4.

The results indicate that in the speed range of 20,000 rpm and up – which is optimum flywheel operational speed – the face seal with an installed length of 0.770 will dissipate approximately 0.2 hp with a maximum seal leakage loss of 0.010 cfm per seal. Total nose loading on this seal is 12.75 lb due to spring preload plus atmospheric pressure against the back of the seal. This load results in a coefficient of friction of 0.045 versus the 0.02 value used in preliminary calculations.



① Varidrive Unit
② Waldron Coupling (Grease lubricated)
③ Strobe-Tachometer
④ Speed Increaser Gearbox (Recirculating oil lube)
⑤ Splined Coupling (Grease lubricated)
⑥ Specimen Seal Holder (See details, Fig. J-2)
⑦ High-Speed Spindle Shaft (Air-oil mist lubrication)
⑧ Vacuum Chamber
⑨ Torque Sensor, Lebow Model 1102-100 (0 to 200 In.-oz. Capacity) Calibrate With Dead Weights
⑩ Mounting Base
⑪ Temperature Recorder (Monitors seal and critical brg temps)
⑫ Daytronic 770 Strain Indicator
⑬ Vacuum Gage
⑭ Vacuum Pump

Fig. J-1 Seal Test Setup

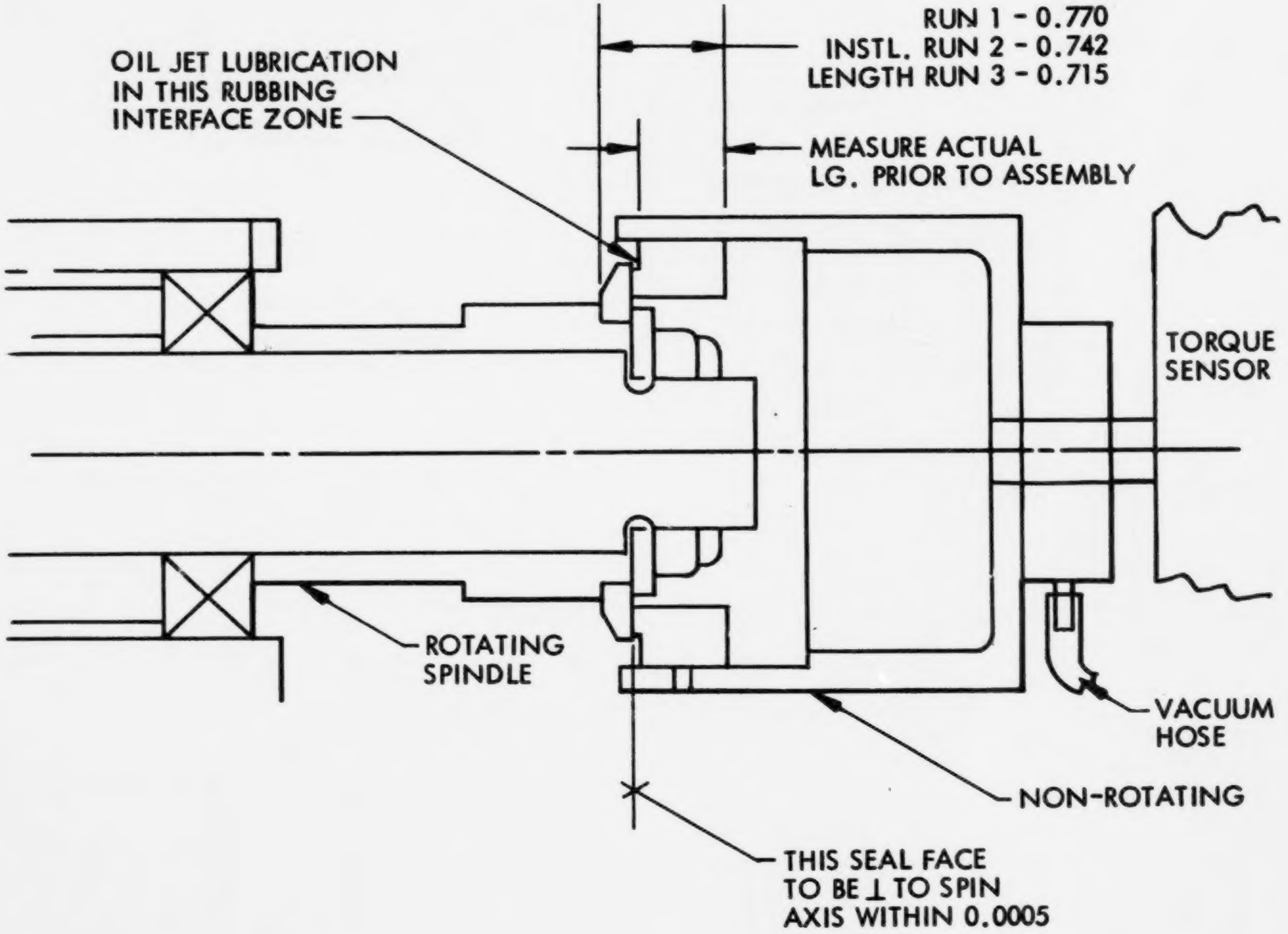

RUN 1 - 0.770
INSTL. RUN 2 - 0.742
LENGTH RUN 3 - 0.715
OIL JET LUBRICATION IN THIS RUBBING INTERFACE ZONE
MEASURE ACTUAL LG. PRIOR TO ASSEMBLY
TORQUE SENSOR
ROTATING SPINDLE
VACUUM HOSE
NON-ROTATING
THIS SEAL FACE TO BE ⊥ TO SPIN AXIS WITHIN 0.0005

Fig. J-2 Face Seal Test

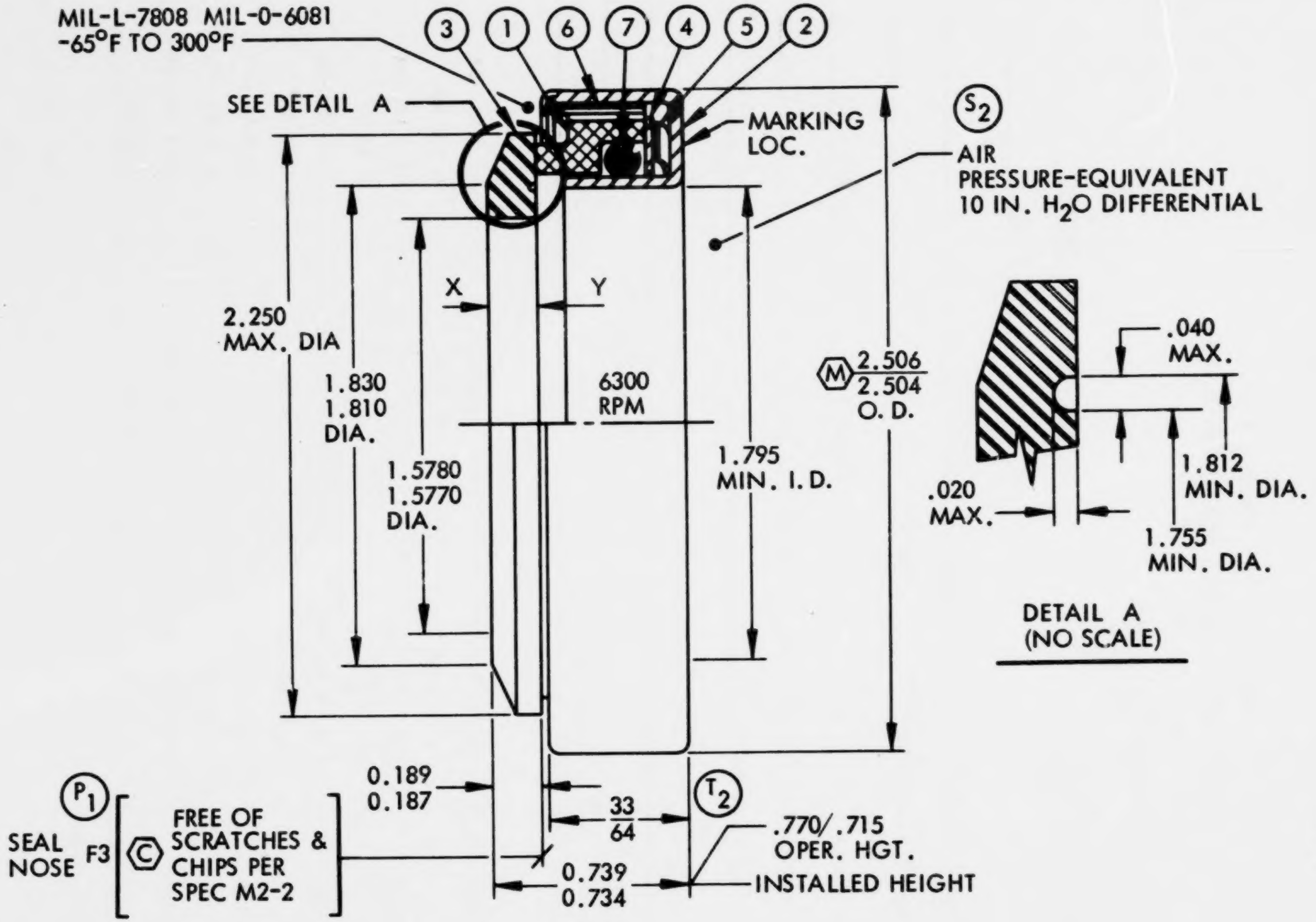

MIL-L-7808 MIL-0-6081
-65°F TO 300°F
SEE DETAIL A
3
1
6
7
4
5
2
MARKING LOC.
S2
AIR PRESSURE-EQUIVALENT 10 IN. H2O DIFFERENTIAL
X
Y
2.250 MAX. DIA
1.830 1.810 DIA.
1.5780 1.5770 DIA.
6300 RPM
1.795 MIN. I.D.
M 2.506/2.504 O.D.
.040 MAX.
1.812 MIN. DIA.
.020 MAX.
1.755 MIN. DIA.
DETAIL A (NO SCALE)
P1
SEAL NOSE F3
C FREE OF SCRATCHES & CHIPS PER SPEC M2-2
0.189 0.187
33/64
T2
.770/.715 OPER. HGT.
0.739 0.734
INSTALLED HEIGHT

Fig. J-3 Details of Seal

Table J-1
FACE SEAL TEST DATA

Friction Drag Test

Date 1/22/72

Recorder M. Helvey

Witness R. Ruth

Ambient Pressure 29.92 psi

Ambient Temperature 68°F

Lubrication:

Type of Oil SAE-20W

Method of Applying Oil Oil-Jet

Oil Flow Rate

Oil Temperature

Speed (rpm)	Seal Installed Length (in.)		
	0.770	0.742	0.715
0[(a)]			
6,000	14.96 in.-oz 0.089 hp	17.50 in.-oz 0.105 hp	32.8 in.-oz 0.195 hp
8,000	14.0 in.-oz 0.11 hp		25.5 in.-oz 0.20 hp
12,000	11.75 in.-oz 0.14 hp	13.78 in.-oz 0.164 hp	21.6 in.-oz 0.25 hp
16,000	10.8 in.-oz 0.17 hp		19.6 in.-oz 0.31 hp
20,000	10.0 in.-oz 0.20 hp	13.0 in.-oz 0.26 hp	18.8 in.-oz 0.37 hp

[(a)] Breakaway torque.

Table J-2

SEAL LEAKAGE TEST

Speed (rpm)	Installed Length (in.)	P_2 (mm Hg)	P_1 (mm Hg)	Weight × 10^{-6}		Δ W	Time (min)	$\Delta W/t$ (lb/min)	cfm
				w_2	w_1				
6,000	0.715	30	4.2	185	28	157	2.5	62.8 × 10^{-6}	0.0084
6,000	0.742	40	4.5	257	30	227	3.5	65.0	0.0086
6,000	0.770	30	4.5	185	30	155	2.5	62.0	0.0083
12,000	0.715	30	4.4	185	29	156	2.5	62.5	0.0084
12,000	0.742	30	4.1	185	25	160	3.0	53.5	0.0072
12,000	0.770	30	4.6	185	26	159	2.8	58.0	0.0078
20,000	0.715	30	8.5	185	52	133	1.5	88.5	0.012
20,000	0.742	30	4.3	185	25	160	2.0	80.0	0.010
20,000	0.770	30	4.6	185	25	159	2.7	58	0.008

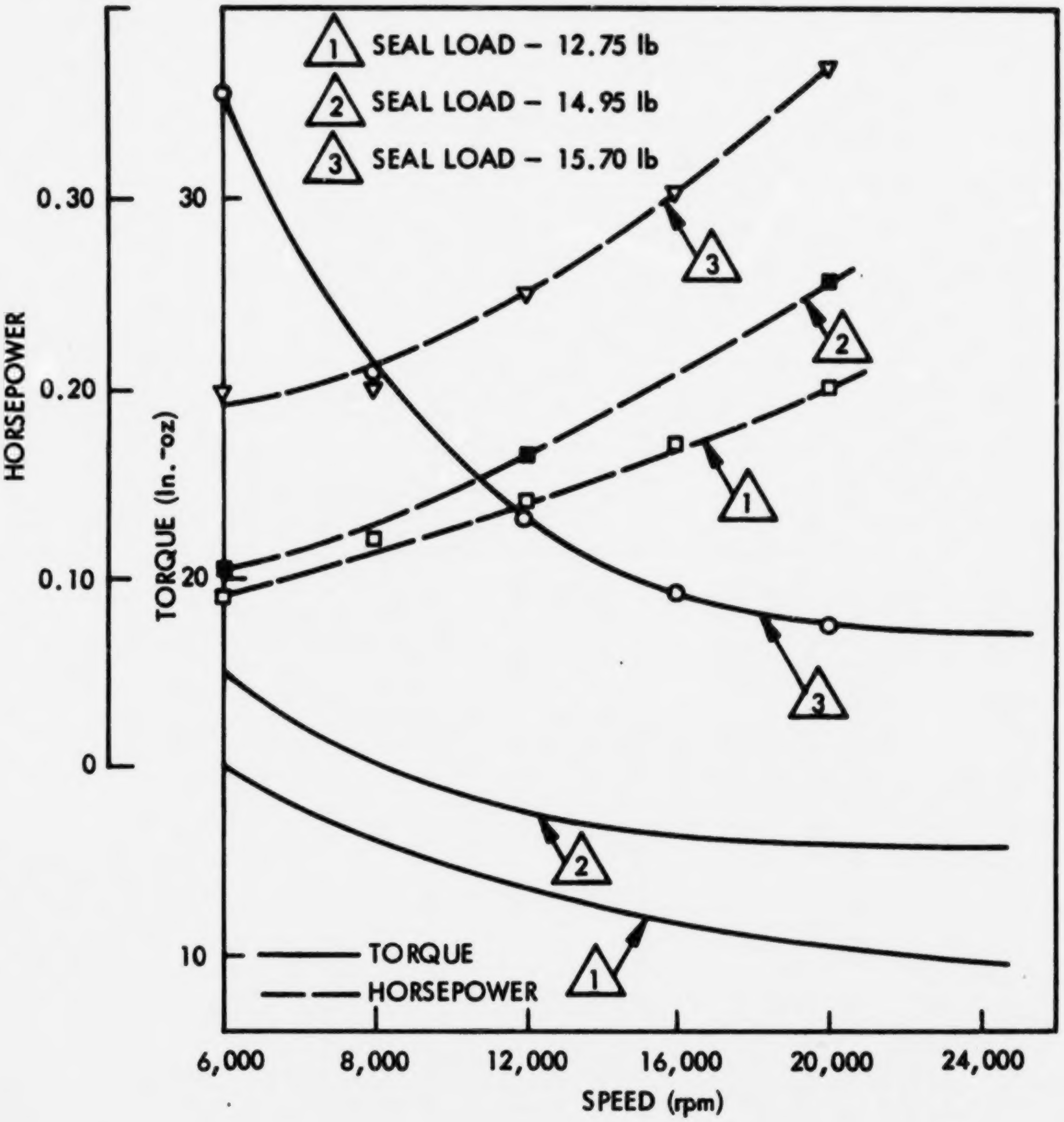


Fig. J-4 Drag Torque and Horsepower Relationships

Appendix K

VACUUM PUMP CALCULATIONS

Vacuum pump calculations for pump sizing and power absorption are presented in this appendix.

Pump calculations using seal leak rate and pump vacuum pressure levels achieved the following test results as performed by LMSC

DATA

$V = 0.04 \text{ ft}^3$

$P_2 = 5 \text{ mm Hg}$

$P_1 = 760 \text{ mm Hg}$

$\Delta T = 0.5 \text{ min}$

$Q_o = 0.5 \text{ Torr (cfm)}$

$Q_c = 0.02 \text{ cfm} = 15.2 \text{ Torr-cfm (2 seals)}$

$C = 1,000$

Then, for pump capacity

$$\text{cfm (load)} = \frac{2.3}{\Delta T} V \lg\left(\frac{P_1}{P_2}\right) + \frac{Q_o + Q_c}{P_2}$$

$$= \frac{2.3}{0.5}(0.04) \lg\left(\frac{760}{5}\right) + \frac{0.5 + 15.2}{5}$$

$$= 0.4 + 3.14 = 3.54 \text{ cfm}$$

$$\frac{1}{\text{cfm}} = \frac{1}{\text{cfm (load)}} + \frac{1}{\text{Conductance}}$$

Since C = 1,000 (see Fig. K-1)

$$\frac{1}{C} \quad \text{is negligible}$$

Pump capacity required = 3.54 cfm

Pump power requirements are shown in Fig. K-2 where the power consumption = 0.17 W-hr/ft^3

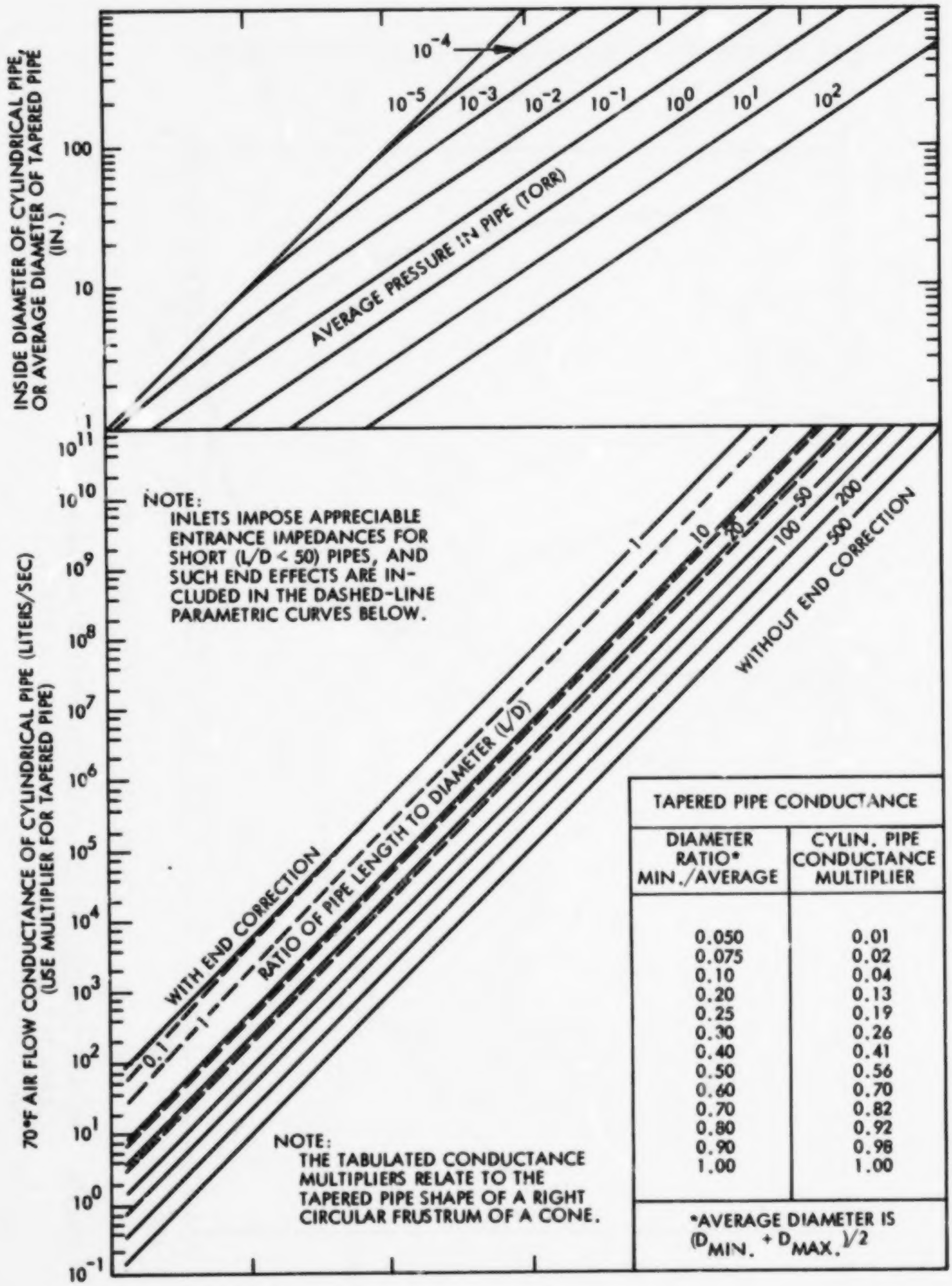
$$3.54 \text{ cfm} \times 60 = 212 \text{ cfh}$$

$$212 \frac{\text{ft}^3}{\text{hr}} \times \frac{0.17 \text{ W-hr}}{\text{ft}^3} \times 1.34 \times 10^{-3} \text{ hp/W} = 0.0484 \text{ hp}$$

Assuming 15% efficiency for the pump because of low pressure, then

$$\text{hp} = \frac{0.0484}{0.15} = 0.323$$

An outgassing rate comparison is given in Fig. K-3.



NOTE:
INLETS IMPOSE APPRECIABLE ENTRANCE IMPEDANCES FOR SHORT (L/D < 50) PIPES, AND SUCH END EFFECTS ARE INCLUDED IN THE DASHED-LINE PARAMETRIC CURVES BELOW.

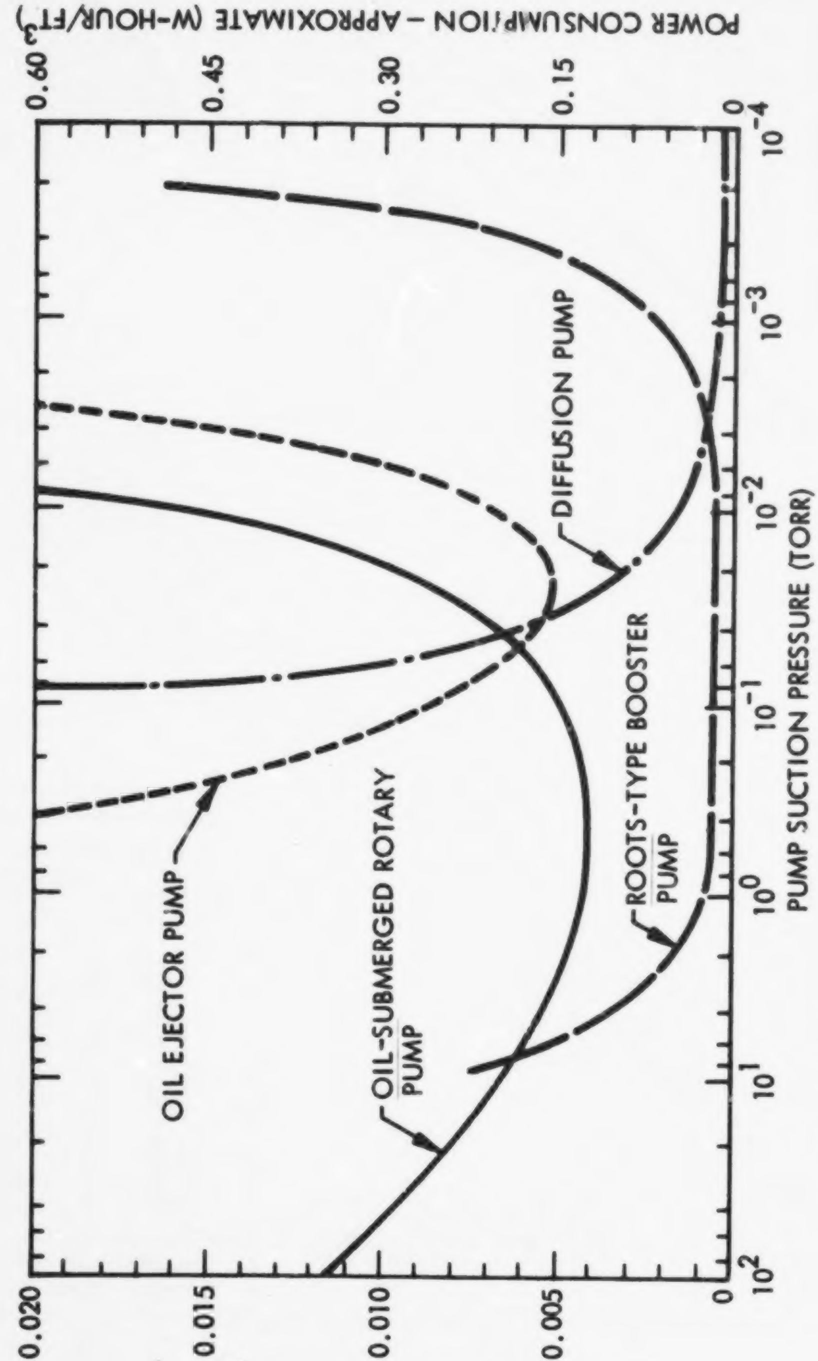
NOTE:
THE TABULATED CONDUCTANCE MULTIPLIERS RELATE TO THE TAPERED PIPE SHAPE OF A RIGHT CIRCULAR FRUSTRUM OF A CONE.

TAPERED PIPE CONDUCTANCE

DIAMETER RATIO* MIN./AVERAGE	CYLIN. PIPE CONDUCTANCE MULTIPLIER
0.050	0.01
0.075	0.02
0.10	0.04
0.20	0.13
0.25	0.19
0.30	0.26
0.40	0.41
0.50	0.56
0.60	0.70
0.70	0.82
0.80	0.92
0.90	0.98
1.00	1.00

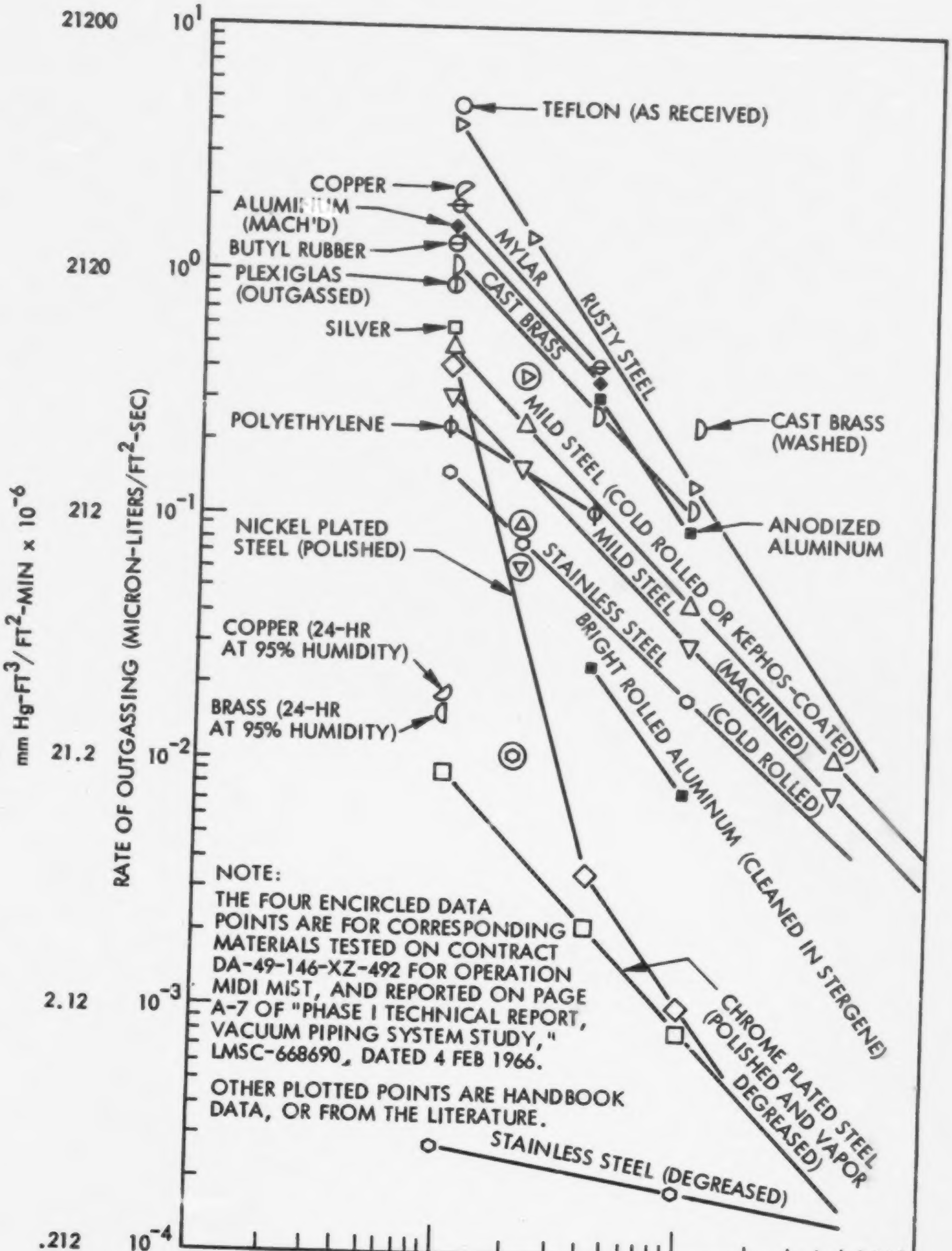
*AVERAGE DIAMETER IS $(D_{MIN.} + D_{MAX.})/2$

Fig. K-1 Improved Method for Determining Vacuum Pipe Flow Conductance



*NOTE: POWER CONSUMPTION IS BASED UPON PUMPING CAPACITY OF THE PUMP, IN LITERS, AT THE SUCTION PRESSURE CONCERNED.

Fig. K-2 Power Consumption of Various Pump Types Relative to the Working Pressure



NOTE:
THE FOUR ENCIRCLED DATA POINTS ARE FOR CORRESPONDING MATERIALS TESTED ON CONTRACT DA-49-146-XZ-492 FOR OPERATION MIDI MIST, AND REPORTED ON PAGE A-7 OF "PHASE I TECHNICAL REPORT, VACUUM PIPING SYSTEM STUDY," LMSC-668690, DATED 4 FEB 1966.

OTHER PLOTTED POINTS ARE HANDBOOK DATA, OR FROM THE LITERATURE.

Fig. K-3 Outgassing Rate Comparison

Appendix L
VACUUM PUMP TEST RESULTS

The results of the vacuum pump tests conducted at LMSC are presented in this appendix.

TEST PROCEDURE

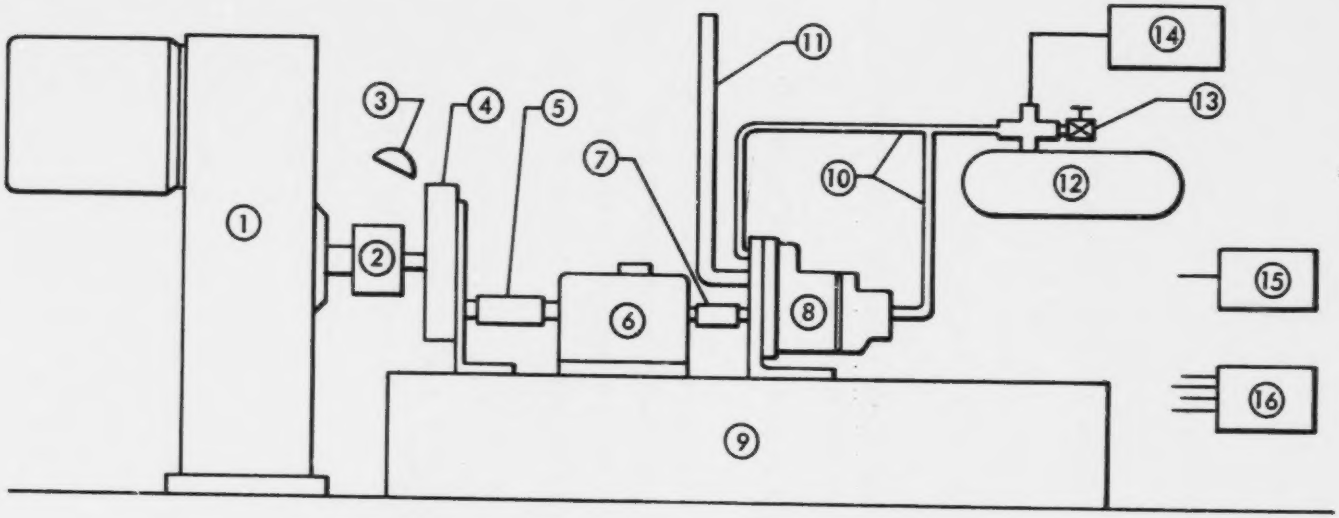
The pump was tested in three different configurations to determine its best arrangement for use as a vacuum pump. The configurations are as follows:

- Test 1 consisted of using one element as a vacuum pump and the second element as a scavenge pump.
- Test 2 consisted of using both elements as a vacuum pump and lubricating the pump with an oil reservoir which was attached to the discharge port.
- Test 3 consisted of using one element as a vacuum pump and removing the other element. Lubrication was accomplished in the same way as in Test 2.

The test objective was to determine the suitability of a gerotor-type oil pump for use as a vacuum pump on high-speed flywheel applications. The test setup for this test is shown by Fig. L-1 (pump test setup).

TEST RESULTS

Test results are shown in Tables L-1, L-2, and L-3, and the pump flow curve is shown in Fig. L-2.



① Varidrive Unit
② Waldron Coupling (grease Lubricated)
③ Strobe-Tachometer
④ Speed Increaser Gearbox (Recirculating oil lube)
⑤ Splined Coupling (Grease lubricated)
⑥ Torque Sensor, Lebow Model 1102-200 (0 – 200 In.-Oz Cap). Dead Weight Calibrated and Air-Oil Mist Lubricated
⑦ Coupling (Grease lubed)
⑧ Test Vacuum Pump
⑨ Base
⑩ Plumbing – Parallel System From Vacuum Chamber to Inlets of Dual Elemet Pump
⑪ Standpipe – Outlet Port of Pump; Minimum Oil Height = 12.0 In.
⑫ Vacuum Chamber
⑬ Vacuum Shutoff Valve
⑭ Vacuum Gage
⑮ Daytronic Model 770 Strain Indicator
⑯ Temperature Recorder (Monitors pump & bearing temps)

Fig. L-1 Pump Test Setup

Table L-1
VACUUM PUMP TEST 1

Date 1/20/72

Recorder M. Helvey

Witness R. Ruth

Type of Pump Gerotor Scavenge Pump

Pump Identification GC 436 M

Pump Configuration 1 Element Oil Pump

1 Element Vacuum Pump

Vacuum Chamber Volume 108 in.^{3}

Ambient Pressure 29.92 psi

Ambient Temperature 68°F

Item	Pump Speed (rpm)			
	5,200	6,000	7,000	8,000
Pumpdown Time (sec)	35	40	40	30
Minimum Pressure Attained (mm Hg)	1.9	2.8	2.9	5.1
Pump Housing Temperature (°F)	100	175	175	215
Torque (in.-oz)	Off Scale; Test Setup Records only up to 100.00 in.-oz			

Table L-2
VACUUM PUMP TEST 2

Date 1/20/72

Recorder M. Helvey

Witness R. Ruth

Type of Pump Gerotor Scavenge Pump

Pump Identification P/N GC 436 M

Pump Configuration Both Elements Vacuum Pump

Vacuum Chamber Volume 108 in.^{3}

Ambient Pressure 29.92 psi

Ambient Temperature 68°F

Item	Pump Speed (rpm)			
	5,200	6,000	7,000	8,000
Pumpdown Time (sec)	37	32	20	17.5
Minimum Pressure Attained (mm Hg)	17.9	21.0	95.0	100.0
Pump Housing Temperature (°F)	148	180	210	210
Torque (in. -oz)	93.02	79.02	66.70	57.40
Horsepower	(0.48)	(0.47)	0.464	0.455

Table L-3
VACUUM PUMP TEST 3

Date 1/20/72

Recorder M. Helvey

Witness R. Ruth

Type of Pump Gerotor Scavenge Pump

Pump Identification P/N GC 436 M

Pump Configuration 1 Element Vacuum Pump

1 Element Removed

Vacuum Chamber Volume 108 in.^{3}

Ambient Pressure 29.92 psi

Ambient Temperature 68°F

Item	Pump Speed (rpm)			
	5,200	6,000	7,000	8,000
Pumpdown Time (sec)	31	25	20	30
Minimum Pressure Attained (mm Hg)	9.5	34	39	30
Pump Housing Temperature (°F)	140	156	160	210
Torque (in.-oz)	46.0	41.7	40.5	31.7
Horsepower	(0.237)	(0.248)	0.281	(0.252)

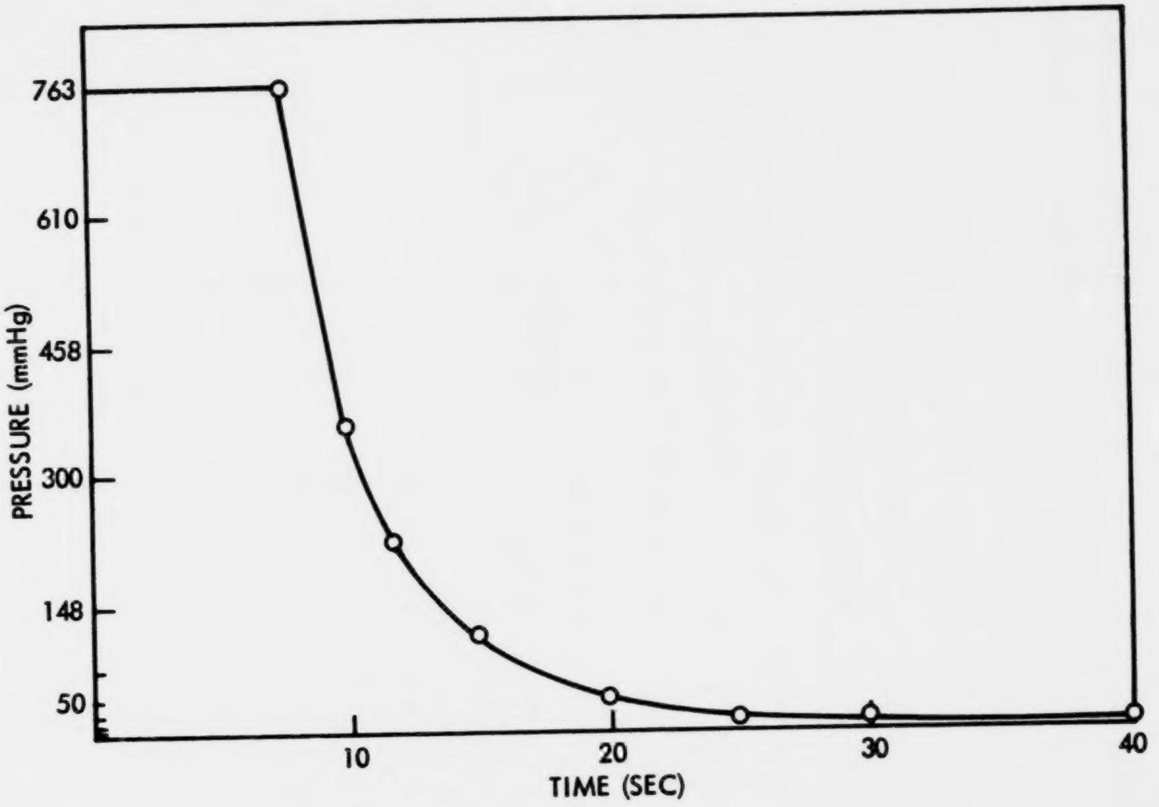


Fig. L-2 Pump Down-Time – Gerotor Pump

CONCLUSIONS

Test results show the pump to be suited to the flywheel system for the following reasons:

- Pump downtime to a useful vacuum level never exceeded 25 sec. A typical pump downtime curve is plotted in Fig. L-2.
- The pump is capable of pumping down and holding air pressure levels below 5 mm Hg.
- Configuration 1 provides the highest vacuum producing capability.
- Temperature stabilized at acceptable levels for all configurations.

Appendix M

LMSC COMPUTER-FORMATTING OF ENGINE TEST DATA AS RECEIVED FROM U.S. BUREAU OF MINES PETROLEUM RESEARCH CENTER

This appendix contains an LMSC computer-formatted version of engine test data as received from the U.S. Bureau of Mines Petroleum Research Center. Following are definitions of pertinent abbreviations and column headings:

ST	Spark timing (°BTC)
MAFR	Measured air-fuel ratio
CAFR	Calculated air-fuel ratio
IAR	Intake air rate (lb/hr)
PO	Power output (bhp)
ER	Exhaust recycle (%)
ET	Exhaust temperature (°F)
MP	Manifold pressure (mm/Hg)
SFC	Specific fuel consumption (lb/bhp-hr)
CO	Carbon monoxide (g/bhp-hr)
HC	Hydrocarbons (g/bhp-hr)
NOX	NO_x measured as NO_2 (g/bhp-hr)

Table M-1

LMSC COMPUTER-FORMATTED VERSION OF U.S. BUREAU OF MINES ENGINE TEST DATA

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PAGE 1
DATE: 11/10 9:02
DATA BASE: /3.0 EMMX/
REPORT FORM: /3.0 EMRI/

ST MAFR CAFR   IAR   PO   ER   EI   MP  SFC     CO     HC    NO

**** ENGINE: A
 *** CATALYST: 0
  ** RECYCLE RATE %:   0
   * PCT. POWER: 10

30 14.7 14.9 201.1  9.9    0 1267  8.7 1.38  23.87   1.07  7.75
30 18.4 17.1 261.1  9.9    0 1279  9.6 1.43  14.56   1.12  9.35
30 16.4 16.4 239.2  9.9    0 1308  9.8 1.47  12.02   1.17  7.02
30 19.7 18.9 300.1  9.9    0 1284 11.5 1.54  28.54  11.63  3.2
20 14.7 14.7 224.4  9.9    0 1343  9.2 1.55  27.59    .83  6.32
20 16.8 16.7 284.5  9.9    0 1393 11.1 1.71   9.75    .63  5.48
20 17.4 17.6   271  9.9    0 1355 10.7 1.58  12.94   1.13  5.83
20 20.9 19.6 388.9  9.9    0 1352   14 1.88  36.92  16.12  1.78
10 14.9 14.7 265.3  9.9    0 1459 10.6  1.8  27.89     .3  5.52
10 16.3 16.6 341.8  9.9    0 1496   13 2.11   8.98    .44  5.54
10 19.3 18.7 404.5  9.9    0 1472 13.5 2.12  15.66   1.87  2.48
10 21.3 19.6 480.9  9.9    0 1441 17.6 2.31  30.72  13.51  2.24

   * PCT. POWER: 25

30 14.8 14.7 273.9 24.4    0 1319 11.2  .76  20.43   1.02  7.88
30 16.4 16.2 296.9 25.1    0 1304 11.9  .72   6.33    .37  7.23
30 18.3 18.3 351.5 25.5    0 1306 13.2  .75   7.46    .39  4.09
30 20.7 20.8 479.8 24.4    0 1319 17.2  .95  14.21   4.91   .80
20 14.8 14.7 310.2 25.4    0 1387   12  .82  19.69    .59  5.59
20 16.2   16 356.3 24.8    0 1380 12.9  .83   5.61     .2  4.97
20 16.5 17.9 417.8 25.4    0 1376 15.2  .89   6.32    .18  3.38
20 21.2 20.3 565.3 25.4    0 1393 19.9 1.05  17.83   6.08  1.01
10 14.4 14.4 341.8 24.7    0 1495 13.2  .96  52.07    .73  3.75
10 16.8 16.3 414.6 25.6    0 1474 16.3  .97   5.05    .04  4.52
10 17.9 17.1 439.7 25.2    0 1455   16  .98   4.94    .16  4.52
10 19.8 18.4 523.9 25.2    0 1462   18 1.05   6.82    .52  2.57

   * PCT. POWER: 50

30   15 14.7 382.7 48.1    0 1323 14.7  .53  20.33   1.08  4.49
30 16.4 16.1 422.5 50.1    0 1274 15.5  .51   5.34     .7 16.51
30 19.6 18.1 499.9 49.1    0 1303 17.2  .51   5.51     .3  6.65
30 20.7 20.1 569.7 49.1    0 1313 20.4  .56   7.79    .70  2.28
20 15.2 14.7   411 48.6    0 1382 15.8  .56     22    .78  6.71
20 16.8 16.1 462.4 44.5    0 1314 16.6  .56   4.06    .32 12.04
20 18.8 18.2 537.6 49.1    0 1378   20  .58   4.05    .14  3.32
20 20.6 18.8 500.6 47.3    0 1389   21   .6    5.3    .26  2.46
10   15 14.6 471.1 48.2    0 1485 18.2  .66  30.33    .34  6.40
10   17 16.1 551.3 49.3    0 1483 19.9  .66   3.12    .05  6.16
10 19.2 17.7 644.7 50.1    0 1450 22.8  .67   3.58    .16  3.92

  ** RECYCLE RATE %:  50
   * PCT. POWER: 10

30 15.3 14.9 241.3  9.9  9.9 1338 10.6  1.6  17.77   2.24  2.79
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Table M-1 (Cont.)

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PAGE 2 11/10

ST MAFR CAFR   IAR   PO   ER   ET   MP  SFC     CO     HC    NO

30 17.4 16.8 294.6  9.9 10.8 1261 12.5 1.71  28.19  12.90  4.77
30 16.9 16.5 286.7  9.9  8.1 1363 11.8 1.72  14.38   4.00   3.1
30 19.5 18.5 317.9  9.9  3.5 1243 12.3 1.65  32.64  15.41  2.03
20 15.4 14.8 265.2  9.9  9.1 1402 11.1 1.74  15.55    .83  3.07
20 16.6 16.6 321.4  9.9  6.4 1400 12.9 1.96  13.12   1.49  3.47
20 17.8 17.5 315.9  9.9  6.4 1363 12.7 1.79  20.95   4.83  4.61
10 15.4 14.8 319.7  9.9  5.5 1495 12.7 2.09      9    .18  3.94
10   17 16.7 377.5  9.9  2.7 1510   14 2.24   9.02    .44  4.51

   * PCT. POWER: 25

30 15.4 14.8 306.3 25.4  6.3 1338 13.6  .78  14.69     .5  4.14
30 16.7 16.1 327.1 24.8  7.1 1299 13.4  .79   7.17    .36  2.82
30 18.6 18.2 379.6 26.4  5.3 1334 14.7  .77   9.05    .59  1.53
30 20.8 20.7 508.1 25.1  2.8 1297 18.7  .97  27.15   13.8   .60
20 15.4 14.8 338.3 25.4  6.9 1400 13.4  .87  12.62    .31  2.95
20   16   16 354.7 25.4  4.9 1408 13.9  .87   5.47    .16  2.89
20 21.7 20.1 578.5 24.8  3.2 1409 20.9 1.07  19.81   5.25  1.06
10 15.2 14.7 408.3 25.4  6.5 1503 16.3 1.06  32.86    .37  2.27
10 17.2 16.4 451.3 25.3  4.8 1507 17.8 1.04   5.56    .02  2.86

   * PCT. POWER: 50

30 15.2 14.8 398.5 48.3  5.8 1330 15.9  .54  13.87    .77  5.76
30 16.9 16.2 429.7 50.1    9 1279 17.2  .51   5.51    .55  4.35
30 18.3 18.2 504.5 51.3  3.6 1329 18.7  .54   6.05    .34  3.59
30 20.9 20.3 569.7 48.2  1.6 1303 21.1  .57   8.91   1.24   1.7
20 15.1 14.8   430 48.2  4.7 1400 17.1  .59  17.27    .59  3.78
20 17.1 16.1 484.6 49.5    7 1336 18.8  .57    5.2    .29  4.04
20 18.9 18.2   553 50.9  2.5 1393 20.5  .57   4.37     .1  2.73

  ** RECYCLE RATE %: 100
   * PCT. POWER: 10

30 14.9 13.9 323.9  9.9   25 1294 15.7  2.2 118.57  55.86   1.5
30 15.6 15.3   337  9.9 24.4 1267 16.5 2.18  92.18  80.19  4.18
30 16.5 16.1 338.2  9.9 16.9 1376 15.3 2.07  46.91  24.38  1.83
30 19.4 18.6 342.4  9.9  7.4 1280 13.9 1.78  48.85   31.6  1.84
20 15.6 14.6 337.8  9.9 18.4 1410 15.1 2.18  33.77   9.41  1.56
20 16.9 16.6 410.6  9.9 10.9 1401 17.3 2.45  39.33  18.59   1.9
20 17.8 17.1 358.4  9.9 13.6 1348 15.1 2.03   38.3  19.94  4.14
20 20.7 19.2 411.2  9.9    5 1318 15.9 2.01  50.94  30.32  1.02
10 18.2 14.8 412.7  9.9 11.3 1554 16.7 2.20  13.35    .86  3.34
10 17.2 16.9   420  9.9  5.4 1544 16.2 2.46  12.81   1.46  3.86
10 19.1 18.6   447  9.9    4 1459 17.2 2.36  23.77   7.48  2.06
10 21.9 19.3 543.5  9.9  3.9 1406   20 2.56   48.2   28.3  1.91

   * PCT. POWER: 25

30 15.9 14.8 384.9 26.1 15.8 1385 16.4  .93  13.97   1.86  1.57
30 16.7 16.2 393.9 25.1 14.4 1377 17.1  .96  12.08   1.81   .46
30   19 18.5 468.2 25.5 12.1 1312 19.3  .97     27   16.8   .63
30 20.8 20.7 521.2 24.6  5.2 1272 19.6 1.02  32.55  24.11   .72
20   16 14.8   421 25.6   13 1454 17.6 1.03  11.12    .64  1.38
```

Table M-1 (Cont.)

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ST	MAFR	CAFR	IAR	PO	ER	ET	MP	SFC	CO	HC	NO
20	16	16.2	437.9	24.8	11.4	1457	17.9	1.1	8.37	.65	1.75
20	18.7	17.9	459.2	24.8	4.8	1403	17.3	.90	8.81	.83	1.97
20	20.2	19.1	545.7	24.8	6.3	1411	20.9	1.09	18.55	1.9	1.17
10	15.7	14.8	484.4	25.4	10.6	1553	20.6	1.22	9.12	.39	2.91
10	17	16.4	503.1	26.1	8.1	1535	20	1.13	6.18	.18	2.35
10	18	17	530.8	25.2	5.1	1528	19.8	1.17	5.47	.2	3.77
10	19.5	18.3	552.9	25.2	3.6	1474	20.4	1.12	9.94	1.51	2.17

* PCT. POWER: 50

ST	MAFR	CAFR	IAR	PO	ER	ET	MP	SFC	CO	HC	NO
30	16.2	14.9	464	49.2	12.4	1364	19.3	.58	9.90	.59	2.16
30	16.5	15.9	493.6	50.1	15.6	1304	20.9	.59	10.78	2.72	1.88
30	19.6	18.4	567.3	50.8	7.6	1338	21.9	.57	10.54	1.92	1.87
30	20.8	20.3	614.2	48.2	4.2	1308	23.2	.61	14.41	5.65	1.15
20	15.6	14.9	485.4	49.7	9	1426	19.6	.63	6.71	.22	2.38
20	17.1	16.1	562	49.5	12.9	1376	22.5	.66	8.09	.92	2.26
20	19.2	18.2	607.5	48.6	6.6	1420	22.5	.65	5.55	.31	1.90
20	19.9	18.8	614.5	47.8	1.2	1401	21.8	.64	5.46	.22	2.53
10	15.9	14.8	530.9	48.8	4.6	1517	20.4	.68	11.52	.12	3.45
10	17	16	513.5	49.5	1.2	1485	19.1	.66	8.81	.15	5.45
10	18.7	17.6	653.8	50.1	1.2	1452	24.1	.7	3.63	.13	4.27

*** CATALYST: 1

** RECYCLE RATE %: 0

* PCT. POWER: 10

ST	MAFR	CAFR	IAR	PO	ER	ET	MP	SFC	CO	HC	NO
30	14.7	15	201.1	9.9	0	1269	8.7	1.38	3.3	.3	6.87
30	18.4	17	261.1	9.9	0	1289	9.6	1.43	4.53	.56	9.35
30	16.4	16.5	239.2	9.9	0	1308	9.8	1.47	3.93	.72	4.8
30	19.7	18.9	300.1	9.9	0	1288	11.5	1.54	4.76	3.46	3.27
20	14.7	14.7	224.4	9.9	0	1341	9.2	1.55	3.58	.34	5.80
20	16.8	16.6	284.5	9.9	0	1391	11.1	1.71	4.67	.56	4.83
20	17.4	17.6	271	9.9	0	1329	10.7	1.58	4.19	.63	5.83
20	20.9	19.6	388.9	9.9	0	1343	14	1.80	6.33	4.12	1.34
10	14.9	14.7	265.3	9.9	0	1958	10.6	1.8	4.11	.18	5.63
10	16.4	16.6	341.8	9.9	0	1483	13.1	2.1	6.26	.4	5.54
10	19.2	18.7	402.3	9.9	0	1452	13.6	2.12	6.57	.65	2.77
10	21.3	19.6	488.9	9.9	0	1436	17.6	2.31	7.96	5.18	2.43

* PCT. POWER: 25

ST	MAFR	CAFR	IAR	PO	ER	ET	MP	SFC	CO	HC	NO
30	14.8	14.7	273.9	24.4	0	1317	11.2	.76	2.09	.21	7.37
30	16.6	16.1	301.4	25.1	0	1306	11.9	.72	2.01	.06	6.7
30	18.3	18.4	351.5	25.5	0	1308	13.2	.75	2.1	.11	4.09
30	20.8	20.9	473.2	25.4	0	1321	17.2	.91	2.83	.68	1.34
20	14.8	14.8	310.2	25.4	0	1387	12	.82	2.27	.11	5.41
20	16.5	16.1	340.7	24.8	0	1384	13.1	.83	2.11	.09	5.03
20	18.5	18	417.8	25.4	0	1379	15.2	.89	2.13	.03	3.38
20	21.2	20.3	565.3	25.6	0	1400	19.4	1.04	3.35	2.11	1.58
10	14.4	14.7	341.8	24.7	0	1461	13.2	.96	2.57	.17	4.01
10	16.8	16.4	414.6	25.6	0	1472	16.3	.97	3.09	.01	4.52
10	17.9	17.2	439.7	25.2	0	1457	16	.98	2.75	.13	4.39
10	19.8	18.5	523.9	25.2	0	1463	18	1.05	3.17	.26	3

Table M-1 (Cont.)

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* PCT. POWER: 50

ST	MAFR	CAFR	IAR	PO	ER	ET	MP	SFC	CO	HC	NO
30	15	14.8	382.7	48.1	0	1324	14.7	.53	1.44	.2	10.2
30	16.4	16.1	422.5	50.1	0	1274	15.5	.51	1.45	.23	15.87
30	19.8	18.3	490.0	49.1	0	1305	17.2	.51	1.55	.07	6.18
30	20.7	20.2	569.7	49.1	0	1313	20.4	.56	1.76	.32	2.45
20	15.2	14.9	409.5	48.6	0	1382	15.8	.56	1.24	.15	6.49
20	16.8	16.1	462.4	49.5	0	1319	16.6	.56	1.61	.12	12.43
20	18.8	18.4	537.6	49.1	0	1378	20	.58	1.87	.06	3.45
20	20.6	18.9	584.4	47.3	0	1380	21	.6	1.78	.11	2.64
10	15	14.8	477.1	48.2	0	1487	18.2	.66	1.7	.08	5.28
10	17	16.1	551.3	49.3	0	1483	19.0	.67	1.51	.04	6.16
10	19.2	17.7	644.7	50.1	0	1453	22.8	.67	2.09	.14	3.92

** RECYCLE RATE %: 50

* PCT. POWER: 10

ST	MAFR	CAFR	IAR	PO	ER	ET	MP	SFC	CO	HC	NO
30	15.3	15	241.3	9.9	9.8	1342	10.7	1.6	4.19	.73	2.6
30	17.4	16.8	294.6	9.9	10.8	1322	12.5	1.71	4.7	3.69	4.77
30	16.6	16.5	286.7	9.9	8	1364	11.9	1.73	4.71	1.33	3.1
30	19.5	18.5	317.9	9.9	3.4	1290	12.3	1.65	5.19	4.84	3.41
20	15.4	14.7	265.2	9.9	9.1	1394	11.1	1.74	4.11	.33	3.07
20	16.6	16.7	321.4	9.9	6.4	1442	13	1.95	5.84	.67	3.47
20	17.8	17.4	319.9	9.9	8.3	1387	12.7	1.79	5.03	1.61	4.46
10	15.4	14.7	319.7	9.9	5.4	150[illegible]	12.7	2.00	4.05	.16	4.31
10	17.1	16.7	377.5	9.9	2.7	1515	14	2.23	6.91	.44	4.8

* PCT. POWER: 25

ST	MAFR	CAFR	IAR	PO	ER	ET	MP	SFC	CO	HC	NO
30	15.4	14.7	307.5	25.4	6.2	1355	13.8	.78	1.74	.11	3.7
30	16.1	16.1	322.7	24.8	7.1	1336	13.4	.81	2	.08	2.84
30	18.8	16.3	379.6	25.2	5.2	1339	14.7	.8	2.58	.3	1.83
30	20.8	20.8	508.1	24.8	2.7	1270	18.7	.98	3.1	2.51	1.24
20	15.4	14.8	3[illegible]9.5	25.4	6.8	1403	13.4	.87	2.48	.06	2.86
20	16	16.2	356.1	25.4	4.9	1407	14.1	.87	2.15	.07	3
20	21.7	20	578.5	24.8	3.1	1406	20.9	1.07	3.54	1.33	1.41
10	15.2	14.7	408.3	25.4	6.2	1504	16.3	1.06	3.36	.15	2.58
10	17.2	16.4	451.3	25.3	4.8	1504	17.8	1.04	3.4	.01	3.13

* PCT. POWER: 50

ST	MAFR	CAFR	IAR	PO	ER	ET	MP	SFC	CO	HC	NO
30	15.2	14.8	398.5	48.3	5.5	1328	15.9	.54	1.49	.17	5.39
30	16.9	16.2	429.7	50.1	9	1280	17.2	.51	1.48	.19	4.26
30	18.3	18.2	504.5	51.3	3.6	1326	18.7	.54	1.5	.09	3.59
30	20.9	20.3	569.7	48.2	1.6	1321	21.1	.57	1.78	.32	1.96
20	15.1	14.9	430	48.2	4.6	1395	17.1	.59	1.37	.12	3.05
20	17.1	16.1	484.6	49.5	6.9	1330	18.8	.57	1.69	.11	4.87
20	18.9	18.2	593	50.9	2.5	1395	20.3	.57	1.81	.03	2.89

** RECYCLE RATE %: 100

* PCT. POWER: 10

ST	MAFR	CAFR	IAR	PO	ER	ET	MP	SFC	CO	HC	NO
30	14.9	14.8	323.9	9.9	22.2	1303	15.7	2.2	7.94	4.74	1.25
30	15.8	15.1	337	9.9	21.7	1274	16.5	2.18	10.65	17.31	3.66

Table M-1 (Cont.)

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ST MAFR CAFR   IAR   PO   ER   EI   HP  SFC     CO    HC    NO

30 16.5   16 338.2  9.9 16.4 1351 15.3 2.07   5.89  4.33  1.83
30 19.4 18.5 342.4  9.9    7 1263 13.9 1.78   5.59  7.11  2.63
20 15.6 14.7 337.8  9.9 17.9 1415 15.1 2.18   5.55  1.46  1.82
20 16.9 16.5 410.6  9.9 10.4 1435 17.2 2.45   7.13  4.29   1.9
20 17.8 17.1 358.4  9.9 13.1 1363 15.1 2.03   5.88  3.99  4.28
20 20.7   19 411.2  9.9  4.8 1332 15.4 2.01    6.9  7.96  1.89
10 16.2 14.7 412.7  9.9 11.3 1554 16.7 2.29   6.39   .34  3.34
10 17.2 16.9   420  9.9  5.4 1523 16.1 2.46   7.29   .58  3.88
10 19.1 18.7   457  9.9    4 1453   17 2.36    7.3  1.86   2.4
10 21.9 19.3 503.5  9.9  3.8 1398   20 2.56   9.54  8.42  2.31

    * PCT. POWER: 25

30 15.9 14.7 384.5 25.8 15.6 1384 16.4  .94   2.63   .38   1.7
30 16.7 16.1 393.9 24.8 14.2 1378 16.8  .95   2.51    .7  1.46
30   19 18.4   470 25.3 11.1 1314 19.3  .98   3.35  2.38    .9
30 20.8 20.6 521.2 24.6  4.8 1270 19.6 1.02   3.61   4.2  1.12
20   16 14.8   421 25.8 12.8 1470 17.6 1.03   3.05   .19  1.63
20   16 16.2 437.9 24.8 11.3 1468 17.9  1.1   2.79   .14  1.82
20 18.7 17.9 459.2 24.8  4.8 1407 17.3  .96   3.34    .3  1.07
20 20.3 18.9 547.8 24.8    6 1411 20.9 1.09   3.36  1.46  1.50
10 15.7 14.7 484.4 25.4 10.6 1554 20.6 1.22   3.54   .11  2.04
10   17 16.4 503.1 26.1  8.1 1535   20 1.13   3.67   .04  2.35
10   18 16.9 530.8 26.2  5.1 1532  9.8 1.17   3.42   .14  4.18
10 19.5 18.3 552.9 25.2  3.5 1473 20.4 1.12   3.34   .52  2.34

    * PCT. POWER: 50

30 16.2 14.8   464 49.2 12.2 1364 19.3  .58   1.71   .13  2.37
30 16.6 15.9 493.6 50.1 15.2 1280 20.9  .59   1.79   .68  1.96
30 19.5 18.3 567.3 50.8  7.4 1340 21.9  .57   1.81   .35  2.21
30 20.6 20.2 614.2 48.2  4.1 1311 23.2  .61   2.02  1.16  1.54
20 15.6 14.9 485.4 49.7  8.9 1630 19.8  .63   1.41   .08  2.06
20 17.2 16.1   562 49.5 12.7 1373 20.5  .66   1.46   .25  2.34
20 19.2 18.3 607.5 48.6  6.6 1418 22.5  .65   2.08   .08  2.23
20 19.9 18.9 614.5 47.8  1.2 1401 21.8  .64   1.84   .08  2.73
10 15.9 14.8   529 48.8  4.6 1517 20.2  .68   1.76   .05  3.42
10   17   16 553.5 49.5  1.2 1485 19.1  .66   5.73   .08  5.22
10 18.7 17.6 653.6 50.1  1.2 1451 24.1   .7   2.12   .12  4.27

**** ENGINE: B
 *** CATALYST: 0
  ** RECYCLE RATE %:   0
   * PCT. POWER: 10

30 14.3 14.6 212.8 10.9    0 1308  9.5 1.36  42.09  2.37  7.73
30 16.3 16.2 247.1 10.4    0 1322 10.5 1.45   12.1   .98  7.23
30 17.8 17.9 286.1 10.6    0 1319 11.9 1.53  16.01  2.25  4.76
30 21.9 21.5 491.5 10.9    0 1271   18 2.05  77.34  73.5   .68
20 14.7 14.5 245.2 10.4    0 1385 10.4  1.6  62.92  3.24  6.27
20 16.5 16.1 286.1   11    0 1416 11.7 1.59  11.18  1.08  6.59
20 18.3   18 339.3 10.9    0 1387 13.5 1.69  15.23  2.13   3.9
20 21.8 20.7 543.2 11.2    0 1345 19.2 2.23  64.84 48.66  1.47
10   15 14.7 290.7 10.4    0 1492 12.5 1.91  42.61  1.98  5.36
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Table M-1 (Cont.)

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ST MAFR CAFR   IAR   PO   ER   EI   HP  SFC     CO    HC    NO

10 16.4   16 339.2   11    0 1493 13.5 1.87  10.73    .7  5.09
10 18.8   18 426.7 10.5    0 1497 16.2 2.17  14.15  1.23  4.03
10 20.8 19.6   597 10.8    0 1496 21.4 2.66  30.61 14.01  2.51

    * PCT. POWER: 25

30 14.5 14.6 294.2 25.2    0 1447 12.2  .81  17.66  2.15 10.49
30 16.3   16 321.2 24.1    0 1305 13.2  .82   8.63  1.06 10.93
30 18.1 17.9 375.6 24.5    0 1291   15  .85  10.41   .80  5.74
30 21.9 21.1 542.8 25.2    0 1287 16.9  .90  28.71 16.16   .81
20 14.4 14.7 320.4 24.6    0 1377   13  .80  22.06  1.49  7.25
20 16.6   16 351.1 24.9    0 1325 13.1   .8   7.61  2.11 11.28
20 18.5 17.6 400.2 24.9    0 1377 17.2  .96   9.41  2.07  3.49
20 21.3 20.5 608.1 24.4    0 1371 22.5 1.17  24.05 13.63  1.32
10 14.9 14.6 372.5 24.6    0 1475   15 1.01  36.95  1.25  5.06
10 19.3 17.6 567.3 24.9    0 1495 21.1 1.18   7.49   .42  3.81

    * PCT. POWER: 50

30 15.1 14.4 451.6 50.5    0 1334 17.4  .59  35.44  2.16 13.12
30 16.9 16.1 487.7   50    0 1317 18.9  .58   6.64   .07 14.08
30 18.7 17.9 540.8   50    0 1298 20.6  .59   7.13   .71  9.37
30 20.7   19 649.8   50    0 1304 23.6  .63   11.5  3.38  4.58
20 15.3 14.5 473.9   50    0 1390 18.2  .62  20.69  1.61 10.77
20   17   16 527.2   50    0 1391   20  .62   6.03   .51 11.44
20 19.2   18 644.2   50    0 1384 23.3  .67   6.43   .40  6.07
10 15.3 14.6 535.8 49.5    0 1483 20.9  .71  29.60   .93  7.85
10 17.2   16 607.1   50    0 1485 23.1  .71    4.8   .31  8.54

  ** RECYCLE RATE %:  50
   * PCT. POWER: 10

30 15.4 14.7 263.1 11.5  7.8 1357 11.5 1.48  19.62  1.57  4.01
30 16.1 16.1   273 10.4  7.5 1357 12.1 1.62  17.03  3.34   3.7
30 17.6 17.5 328.3 10.7  8.2 1343 14.4 1.74  28.46  11.4   2.1
20 15.3 14.8 300.8 10.4  9.4 1448 13.1 1.80   17.5  1.98  2.85
20 16.2   16 310.4   11  6.7 1425 13.5 1.74  13.61  1.81  3.23
20 18.4 17.8 366.1 10.2    5 1410 15.1 1.95  27.03  4.92  2.18
10 15.3 14.8   320 10.4  4.1 1517 13.8 2.08    4.1   .36  4.57
10 16.5   16 366.8 10.3  4.1 1518 14.9 2.15  11.07   .61  4.75

    * PCT. POWER: 25

30 15.9 14.6 340.1 25.2 10.2 1350 14.6  .85   9.16  1.27   3.4
30   16   16 339.1 25.1  3.2 1308 13.7  .82   8.25  1.06  8.04
30 18.2 17.9 397.6 24.6  3.7 1306 15.9  .89  11.72   .85  3.93
30 20.7 20.3 552.4 24.4    4 1245 22.6  1.1  38.56 45.37    .6
20 15.2 14.8 349.8 24.6  6.4 1407 14.7  .93     12   .95  3.58
20 16.4   16 339.8 24.4  5.8 1328 14.5  .85    8.5  1.17  4.65
20 18.9 17.6 458.9 24.9  2.3 1389 17.5  .98   4.81   .68  3.08
10 15.5 14.8 417.6 24.6    5 1504 17.2  1.1  20.71   .82  3.75

    * PCT. POWER: 50
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Table M-1 (Cont.)

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ST MAFR CAFR   IAR   PO   ER   ET   HP  SFC     CO     HC    NO

30   15 14.5 459.2 50.6  6.6 1336 18.8   .6  31.33   1.96  7.11
30 16.8   16 504.6   50  2.3 1326 20.2   .6   7.18    .93  8.29
30 18.9   18 586.5   50  3.5 1315 27.5  .62    8.4    .83  5.87
20 15.4 14.7 505.2   50  5.5 1404 20.5  .65   20.5    1.2  6.09
20 17.1   16 542.7   50  3.6 1395 21.5  .63   5.56    .45  7.38

  ** RECYCLE RATE %: 100
   * PCT. POWER: 10

30   15 14.3 341.4 11.6 20.8 1370 15.9 1.96  60.92  26.35  1.57
30 15.8 15.6 341.4 10.4 18.5 1360 16.1 2.07  60.04  30.91  1.75
30   17 16.7 391.5   11 17.2 1319 17.7 2.09  60.06  57.13  1.57
30 21.6 21.3 518.5 11.3  3.6 1218 19.2 2.13  83.11 128.34   .69
20   16 14.4 421.4 10.4 19.2 1437   20 2.53  57.35  25.02  1.54
20 16.3 15.9 381.4   11 13.6 1458 17.5 2.12  27.23   7.65  1.85
20 18.2 17.6 438.1   11 11.2 1405 18.8 2.19   41.6  22.77  1.36
20 20.7 19.7 545.4 11.4  5.6 1346   21 2.31  64.35  52.32  1.45
10 15.9 14.8   413 10.4    9 1509 17.5 2.48  21.09   1.81  3.16
10 15.5   16 424.6 10.7  8.4 1506 17.7 2.41  13.80   1.33  3.65
10 18.7 17.4 431.1 10.3   .6 1501 16.5 2.23  14.47   1.43   3.8
10 19.7   19 572.4 10.2  3.9 1502 22.2 2.83  32.27  17.62  2.97

   * PCT. POWER: 25

30 15.4 14.4 412.4 24.9   20 1379 14.7 1.07  26.03   9.62  1.52
30 16.4   16 351.8 24.6  8.2 1331 15.4  .87   9.44   1.12  3.82
30 18.4   18 427.9 24.4  6.7 1326 17.6  .96  15.76   1.93     2
30 20.2 19.7 547.4 24.4  9.3 1258 22.7 1.11  38.51  44.55    .6
20 15.6 14.8 409.8 25.2 11.2 1447 17.7 1.04  13.76   1.01  2.05
20 16.6 15.8 436.4 24.7 17.7 1372   20 1.06  27.53  12.27  1.29
20   18 17.5 535.3 24.9 10.3 1400 22.7 1.19   24.7  11.02  1.47
20 21.2 20.3 624.4 24.4  3.2 1351 23.5 1.21  36.05  23.31  1.16
10 16.4 14.8 513.3 24.6  9.0 1502 21.3 1.28  13.69    .67  2.65
10 19.5 17.8 612.7 24.9  2.9 1512 23.4 1.26  10.82    1.8  3.55

   * PCT. POWER: 50

30 15.7 14.7 516.6 51.1 13.9 1373 27.5  .64  16.43   1.35  2.54
30 17.1 16.1 560.5   50 10.9 1356 23.3  .66   6.40    1.5  3.68
30 18.8 17.9 617.6   50  7.1 1323   24  .66  10.47   1.41  3.57
30 20.8 19.4 701.3   50  3.7 1306 25.6  .67  16.34   6.23  2.49
20 16.1 14.8 560.2 48.6 11.7 1435 23.8  .72  12.21    .82  3.34
20 17.5   16 587.1   50  7.3 1414 23.9  .67    6.5    .57  4.08
20 19.8   18 679.8   50  1.6 1395 24.5  .69   7.23    .59  4.65
10 15.8 14.8 595.5 49.5  4.1 1509 23.4  .76  14.14     .5  5.55
10 17.7   16 653.5 49.5  2.3 1498 24.7  .75   4.55    .36  6.87

 *** CATALYST: 1
  ** RECYCLE RATE %:   0
   * PCT. POWER: 10

30 14.3 14.7 212.8 10.9    0 1304  9.5 1.36   3.35     .5  6.99
30 16.1 16.2 244.8 10.4    0 1321 10.4 1.45   3.27    .22  6.81
30 17.8 17.9 280.1 10.6    0 1319 11.9 1.53   3.78    .37  5.39
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Table M-1 (Cont.)

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ST MAFR CAFR   IAR   PO   ER   ET   HP  SFC     CO     HC    NO

30 21.9   21 491.5 10.9    0 1256   18 2.05   8.06  27.48   1.7
20 14.7 14.6 245.2 10.4    0 1377 10.4  1.6    3.6    .78  5.02
20 16.5 16.1 280.1   11    0 1393 11.7 1.59   3.77    .29  6.79
20 18.3 17.9 359.3 10.9    0 1389 13.5 1.69   4.74    .47  4.37
20 21.8 20.6 543.2 11.2    0 1344 19.2 2.23   8.72  18.59  1.65
10   15 14.7 200.7 10.4    0 1507 12.3 1.91   4.13    .53  5.58
10 16.4 16.1 3[illegible]0.2   11    0 1491 13.5 1.87   4.43    .23  6.58
10 18.6 17.9 426.7 10.5    0 1501 16.2 2.17  14.15    .26  4.34
10 20.8 19.3   597 10.8    0 1509 21.4 2.66   8.43  17.43  2.94

   * PCT. POWER: 25

30 14.7 14.6 240.8 25.2    0 1322 12.2  .81   1.82    .74  9.74
30 16.2   16 320.2 23.8    0 1301 13.4  .83   1.94    .22 10.68
30 18.1 17.9 375.6 24.4    0 1290 14.6  .85   2.64    .15  5.74
30 22.1 21.1 540.7 25.2    0 1276 20.1  .97   3.65   3.32  1.54
20 14.8 14.7 320.4 24.6    0 1301   13  .85   2.18     .3  6.05
20 16.6 16.1 371.1 24.9    0 1319 13.2   .8   1.92    .92 10.42
20 18.7 17.9 452.5 24.9    0 1374 17.1  .95   2.80    .37  3.78
20 21.1 20.5 604.3 24.4    0 1364 22.3 1.18   4.27   3.60  1.97
10 14.7 14.7 368.2 24.6    0 1875   15 1.01   2.57    .22   5.7
10 19.5 17.9 569.5 24.9    0 1492 21.1 1.17   3.49    .16  4.09

   * PCT. POWER: 50

30 15.1 14.6 451.6   50    0 1337 17.4  .59   1.64    .42 13.24
30   17 16.1 493.2   50    0 1315 18.8  .58   1.61     .2 15.07
30 18.5 17.9 548.5   50    0 1298 20.7  .59   1.67    .24  9.21
30 20.6 19.2 649.8   50    0 1307 23.6  .63   1.98   1.78  4.82
20 15.3 14.7 473.5   50    0 1391 18.1  .62   1.70    .34 10.77
20   17 16.1 527.2   50    0 1384   20  .62   1.52    .14 11.12
20 19.2   18 644.2   50    0 1380 23.3  .67   1.85    .18  6.21
10 15.3 14.7 535.8 49.5    0 1489 20.9  .71   2.11    .21   8.1
10 17.2 15.4 607.1   50    0 1484 23.1  .71   1.86     .1  8.26

  ** RECYCLE RATE %:  50
   * PCT. POWER: 10

30 15.4 14.8 263.1 11.5  7.8 1357 11.5 1.48   3.92    .54  4.01
30 16.2 16.1   273 10.4  7.5 1360 12.1 1.61   3.65   1.02   3.8
30 17.6 17.5 328.3 10.7  8.1 1334 14.4 1.74    4.7   2.46  2.92
20 15.3 14.7 300.8 10.4  9.4 1449 13.3 1.89   4.01    .63  2.85
20 15.2   16 310.4   11  6.6 1438 13.5 1.74   4.06    .45  3.55
20 18.4 17.8 360.1 10.2    5 1414 15.1 1.95    5.8   1.23  2.86
10 15.3 14.8   330 10.4  4.1 1529 13.8 2.06    4.1    .36  4.57
10 16.5   16 366.8 10.3  3.6 1518 14.9 2.15   5.12     .2  5.16

   * PCT. POWER: 25

30 15.8 14.6 339.2 25.2  9.9 1348 14.9  .85   1.94    .42  3.34
30   16 15.9 371.4 24.9  3.2 1308 13.7  .83   1.86     .2  7.84
30 18.1 17.9 397.6 24.6  3.6 1312 14.8  .89   2.76    .16  4.05
30 20.9 19.8 584.7 24.4  3.5 1249 22.7 1.09   4.09   11.4  1.03
20 15.2 14.7 369.8 24.6  6.3 1409 14.7  .93   2.37    .16  3.57
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Table M-1 (Cont.)

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SI MAFR CAFR   IAR   PO   ER   ET   MP  SFC    CO    HC    NO

20 16.4   16 339.8 24.4  5.8 1324 14.5  .85  2.01   .39  4.58
20 18.9 17.5 456.6 24.9  2.3 1389 17.6  .97  2.97   .23  3.42
10 15.5 14.7 417.6 24.6  4.9 1500 17.2  1.1  2.91   .15  3.45
10 19.4 17.8 612.6 24.9  2.9 1512 23.4 1.26 10.82   1.8  3.55

   * PCT. POWER: 50

30   15 14.6 459.2 50.7  6.3 1339 18.8   .6  1.56   .37   7.2
30 16.9   16 504.6   50  2.3 1327 20.2   .6  1.64    .2  8.20
30 16.8   18 584.2   50  3.7 1313 22.5  .62  1.78   .23  6.21
20 15.5 14.7 507.2 50.5  5.4 1407 20.5  .65  1.82   .24  6.06
20 17.1   16 542.7   50  3.6 1397 21.5  .63  1.67   .12  7.38

  ** RECYCLE RATE %: 100
   * PCT. POWER: 10

30   15 14.6 341.4 11.6 19.7 1371 16.5 1.96  6.83  4.36   1.8
30 16.1 15.4 346.1 10.4 17.4 1360 16.1 2.06  7.73  6.83  2.03
30   17 16.6 391.5   11   16 1309 17.7 2.09  5.94 11.76   1.9
30 21.6 20.6 515.5 11.3    3 1225 19.2 2.13  8.45 45.98  1.39
20 15.9 14.6 419.7  2.7 18.6 1443 19.9 2.53  6.16  4.52  1.84
20 16.3   16 381.9   11 13.4 1460 17.5 2.12  5.32  1.67  2.38
20 18.2 17.5 438.1   11 10.7 1405 18.9 2.19  6.44  5.01  2.12
20 20.7 19.5 595.4 11.4  5.2 1341   21 2.31  8.87 20.96  1.81
10 15.9 14.7   413 10.4    9 1570 17.5 2.48  5.68   .54  3.61
10 16.5   16 424.6 10.7  8.4 1555 17.7 2.41  5.74    .4  3.95
10 18.7 17.9 431.1 10.3   .6 1500 16.5 2.23  6.56   .45  4.12
10 19.7   19 572.4 10.2  3.9 1498 22.2 2.83  9.55  7.66  2.97

   * PCT. POWER: 25

30 15.6 14.5 416.9 24.9 19.2 1367 20.1 1.07  2.72  1.69  1.92
30 16.4 16.1 351.8 24.5  8.1 1329 15.4  .86  2.07   .22  3.85
30 18.4 17.9 427.9 24.4  6.6 1328 17.7  .96  3.01    .3  2.67
30 20.2 19.6 545.9 24.4  8.3 1256 22.6 1.11  4.02  7.65  1.19
20 15.6 14.7 408.2 25.2   11 1409 17.7 1.04  2.71   .22  2.35
20 16.6 15.6 436.4 24.7   17 1371   20 1.06  3.21  1.79  1.35
20   18 17.3 535.5 24.9  9.7 1402 22.8  1.2  3.69  1.78  2.13
20 21.2 20.1 626.7 24.4    3 1364 23.7 1.21  4.38  5.44  1.55
10 16.5 14.7 515.2 24.4  9.9 1551 21.3 1.28  3.63   .16  2.82
10 19.6 17.8 612.6 24.9  2.9 1516 23.1 1.26  3.90   .31  3.55

   * PCT. POWER: 50

30 15.7 14.7 516.6 51.1 13.6 1374 22.5  .64  1.74   .33  2.81
30   17 16.1 566.5   50 10.9 1355 23.2  .67  1.84   .26  4.03
30 18.6 17.9 615.1   50    7 1327 24.3  .66  1.90   .45  4.02
30 20.9 19.3 705.8   50  3.6 1310 25.8  .67  2.28  1.96  3.52
20   16 14.7 558.1 48.6 11.7 1437 23.8  .72  2.08   .21   3.5
20 17.5 16.1 587.1   50  7.3 1415 23.9  .67   1.8   .16  4.17
20 19.6   18 677.5   50  1.6 1392 24.4  .69  2.19    .2  4.78
10 15.8 14.7 595.5 49.5  4.1 1506 23.4  .76  2.07   .13  5.69
10 17.7 16.1 653.5 49.5  2.3 1500 24.7  .75  2.03    .1  6.87
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Appendix N

ENGINE TEST DATA – RATIOS OF EMISSIONS TO SPECIFIC FUEL CONSUMPTION

This appendix contains a series of tables presenting data showing the relationship between emissions and specific fuel consumption. Following are definitions of pertinent abbreviations and column headings:

SPK TIM	Spark timing (°BTC)
MEAS A-F	Measured air-fuel ratio
CO-SFC	Carbon dioxide(g)/lb fuel
HC/SFC	Hydrocarbons(g)/lb fuel
NOX/SFC	Oxides of nitrogen(g)/lb fuel
E	Engine
C	Catalyst
RR	Exhaust recirculation rate
PP	Percent power

Table N-1

ENGINE TEST DATA, SHOWING RELATIONSHIP BETWEEN EMISSIONS AND SPECIFIC FUEL CONSUMPTION

```
PAGE 1
DATE: 11/12 17:21
DATA BASE: /3.0 EMMX/
REPORT FORM: /R/

SPK    MEAS      CO         HC        NOX
TIM    A-F       SFC        SFC       SFC

***** E: A
 **** C: 0
   ** RR:   0
    * PP: 10

   30   14.7   17.2971     .7754    5.6159
   30   18.4   10.1818     .7832    6.5385
   30   16.4    8.1769     .7959    4.7755
   30   19.7   18.5325    7.5519    2.0909
   20   14.7   17.8000     .5355    4.0774
   20   16.8    5.7018     .3684    3.2047
   20   17.4    8.1699     .7152    3.6899
   20   20.9   19.6383    8.5745     .9468
   10   14.9   15.4944     .1667    3.0667
   10   16.3    4.2559     .2085    2.6256
   10   19.3    7.3868     .8821    1.1698
   10   21.3   13.2987    5.8485     .9697

    * PP: 25

   30   14.8   26.8816    1.3421   10.3684
   30   16.4    8.7917     .5139   10.0417
   30   18.3    9.9467     .5200    5.4533
   30   20.7   20.2211    3.1684     .9368
   20   14.8   24.0122     .7195    6.8171
   20   16.2    6.7590     .2651    5.9800
   20   18.5    7.1011     .2927    3.7978
   20   21.2   16.9810    5.7905     .9619
   10   14.4   54.2396     .7604    3.9062
   10   16.6    5.2062     .0412    4.6598
   10   17.9    5.0408     .1633    4.6122
   10   19.8    6.4952     .4952    2.4476

    * PP: 50

   30   15.0   38.3565    2.0377    8.4717
   30   16.4   10.4706    1.3725   32.3725
   30   19.8   10.8039     .5882   13.0392
   30   20.7   13.9107    1.4107    4.0714
   20   15.2   39.2857    1.3929   11.9821
   20   16.8    8.8571     .5714   22.3929
   20   18.8    7.6724     .2414    3.7241
   20   20.6    8.8333     .4333    4.1000
   10   15.0   45.9545     .5152    9.8333
   10   17.0    4.7273     .0758    9.3333
   10   19.2    5.3433     .2388    5.8507

   ** RR:  50
    * PP: 10
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Table N-1 (Cont.)

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SPK    MEAS      CO         HC        NOX
TIM    A-F       SFC        SFC       SFC

   30   15.3   11.1063    1.4000    1.7437
   30   17.4   16.4854    7.5965    2.7895
   30   16.9   11.2674    2.9012    1.8923
   30   19.5   19.7818    9.3394    1.7758
   20   15.4    8.9368     .4770    1.7648
   20   16.6    6.6939     .7602    1.7704
   20   17.8   11.7263    2.6983    2.5754
   10   15.4    4.3062     .0861    1.8852
   10   17.0    4.4286     .1964    2.0134

    * PP: 25

   30   15.4   18.8333     .6410    5.3077
   30   16.7    9.0759     .4567    3.5696
   30   18.6   11.7532     .7662    1.9870
   30   20.8   27.9897   14.2268     .7113
   20   15.4   14.5057     .3563    3.3908
   20   16.0    6.2874     .1839    3.3218
   20   21.7   18.3271    4.9065     .9907
   10   15.2   31.0000     .3491    2.1415
   10   17.2    5.3462     .0192    2.7500

    * PP: 50

   30   15.2   25.6852    1.4259   10.6667
   30   16.9   10.8039    1.0784    8.4902
   30   18.3   11.2037     .8296    6.6481
   30   20.9   15.6316    2.1754    2.9825
   20   15.1   29.2712    1.0000    6.4068
   20   17.1    9.1228     .5088    8.6667
   20   18.9    7.6567     .1754    4.7895

   ** RR: 100
    * PP: 10

   30   14.9   53.8955   25.3909     .6818
   30   15.6   42.2844   36.7844    1.9174
   30   16.5   22.6018   11.7778     .8841
   30   19.4   27.4697   17.7528    1.0337
   20   15.6   15.4908    4.3165     .7156
   20   16.9   16.0531    7.5878     .7755
   20   17.8   18.8670    9.8277    2.0396
   20   20.7   25.3433   15.0846     .7065
   10   18.2    5.8297     .3755    1.4585
   10   17.2    5.2073     .5935    1.5772
   10   19.1   10.0729    3.1695     .8729
   10   21.9   18.8281   11.0547     .7461

    * PP: 25

   30   15.9   15.0215    2.0000    1.6882
   30   16.7   13.8191    1.9255     .5745
   30   19.0   27.8351   17.3196     .6495
```

Table N-1 (Cont.)

'PAGE 3 11/12

SPK TIM	MEAS A-F	CO/SFC	HC/SFC	NOX/SFC
30	20.8	31.9118	23.6373	.7059
20	16.0	10.7961	.6214	1.3398
20	16.0	7.6091	.5909	1.5909
20	18.7	8.8990	.8384	1.9899
20	20.2	17.0183	1.7431	1.0734
10	15.7	7.6754	.3197	2.3652
10	17.0	5.4690	.1593	2.0796
10	18.0	4.6752	.1709	3.2222
10	19.5	8.8750	1.3482	1.9375
* PP: 50				
30	16.2	17.2241	1.0172	3.7241
30	16.5	18.2712	4.6102	3.1864
30	19.6	18.4912	3.3684	3.2807
30	20.8	23.6230	9.2623	1.8452
20	15.6	10.6508	.3492	3.7778
20	17.1	12.2576	1.3939	3.4242
20	19.2	8.5385	.4769	3.0615
20	19.9	8.5312	.3437	3.4531
10	15.9	16.9412	.1765	5.0735
10	17.0	13.3485	.2273	8.2424
10	18.7	5.1857	.1857	6.0286
*** C: 1				
** RR: 0				
* PP: 10				
30	14.7	2.3913	.2174	4.9420
30	18.4	3.1678	.3916	6.5385
30	16.4	2.6735	.4898	3.2653
30	19.7	3.0909	2.2468	2.0909
20	14.7	2.3097	.2194	3.8007
20	16.8	2.7310	.3275	2.8246
20	17.4	2.6519	.3987	3.6890
20	20.9	3.3670	2.1915	.7128
10	14.9	2.2833	.1000	3.1278
10	16.4	2.4810	.1905	2.6381
10	19.2	3.0991	.3066	1.3066
10	21.3	3.4459	2.2424	1.0519
* PP: 25				
30	14.8	2.7500	.2763	9.6974
30	16.6	2.7917	.0833	9.3058
30	18.3	2.8000	.1467	5.4533
30	20.4	3.1099	.7473	1.4725
20	14.8	2.7683	.1341	8.5976
20	16.5	2.5422	.1084	6.0602
20	18.5	2.3933	.0337	3.7978
20	21.2	3.2212	2.0288	1.5192
10	14.4	2.6771	.1771	4.1771
10	16.8	3.1856	.0103	4.6598

Table N-1 (Cont.)

'PAGE 4 11/12'

SPK TIM	MEAS A-F	CO/SFC	HC/SFC	NOX/SFC
10	17.9	2.8061	.1327	4.4796
10	19.8	3.0190	.2476	2.8571
* PP: 50				
30	15.0	2.7170	.3774	19.2453
30	16.4	2.8431	.4510	31.1176
30	19.8	3.0392	.1373	12.1176
30	20.7	3.1429	.5714	4.3750
20	15.2	2.3036	.2679	11.5893
20	16.8	2.8750	.2143	22.1964
20	18.8	3.2241	.1034	5.9483
20	20.6	2.9667	.1833	4.4000
10	15.9	2.5758	.1212	8.9900
10	17.0	2.2879	.0606	9.3333
10	19.2	3.1194	.2090	5.8507
** RR: 50				
* PP: 10				
30	15.3	2.6187	.4562	1.6250
30	17.4	2.7485	2.1579	2.7895
30	16.8	2.7225	.7680	1.7919
30	19.5	3.1455	2.9333	2.0667
20	15.4	2.3621	.1897	1.7644
20	16.6	3.0154	.3436	1.7795
20	17.8	2.8101	.8994	2.7151
10	15.4	2.3684	.0766	2.0622
10	17.1	3.0987	.1973	2.1525
* PP: 25				
30	15.4	2.2308	.1410	4.7436
30	16.1	2.4691	.0988	3.5556
30	18.8	3.2250	.3750	2.2875
30	20.8	3.1633	2.5612	1.2653
20	15.4	2.8506	.0690	3.2874
20	16.0	2.4713	.0805	3.4483
20	21.7	3.3084	1.2430	1.3178
10	15.2	3.1698	.1415	2.4340
10	17.2	3.2692	.0096	3.0096
* PP: 50				
30	15.2	2.7593	.3148	9.9815
30	16.9	2.9029	.3725	8.3529
30	18.3	2.7778	.1667	6.6481
30	20.9	3.1404	.5614	3.4386
20	15.1	2.3220	.2034	6.6949
20	17.1	2.9649	.1930	8.5439
20	18.9	3.1754	.0526	5.0702
** RR: 100				

Table N-1 (Cont.)

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SPK TIM	MEAS A-F	CO/SFC	HC/SFC	NOX/SFC
* PP: 10				
30	14.9	3.6091	4.4273	.5682
30	15.6	4.8899	7.9404	1.6789
30	16.5	2.8454	2.0918	.8041
30	19.4	3.1404	3.9066	1.4775
20	15.6	2.5459	.8991	.8349
20	16.9	2.9102	1.7510	.7755
20	17.8	2.8966	1.9655	2.1084
20	20.7	3.4328	3.9602	.9403
10	16.2	2.7904	.1485	1.4585
10	17.2	2.9634	.2358	1.5772
10	19.1	3.0932	.7801	1.0169
10	21.9	3.7266	3.2891	.9102
* PP: 25				
30	15.9	3.0106	.4043	1.8085
30	16.7	2.6421	.2105	1.5368
30	19.0	3.4184	2.4286	1.0102
30	20.8	3.5392	4.1176	1.0980
20	16.0	2.9612	.1845	1.5825
20	16.9	2.5364	.1273	1.6545
20	18.7	3.3737	.3035	1.9899
20	20.3	3.0826	1.3394	1.4587
10	15.7	2.9016	.0902	1.6721
10	17.0	3.2478	.0354	2.0798
10	18.0	2.9231	.1197	3.5726
10	19.5	2.9821	.4643	2.0893
* PP: 50				
30	16.2	2.9483	.2741	4.0862
30	16.6	3.0339	1.1525	3.3220
30	19.6	3.1754	.6140	3.8772
30	20.8	3.3115	1.9916	2.5248
20	15.6	2.2331	.1270	3.9048
20	17.2	2.9697	.3788	3.5455
20	19.2	3.2004	.1231	3.4308
20	19.9	2.8750	.1406	4.2656
10	15.9	2.5882	.0735	5.1765
10	17.0	8.6818	.1212	7.9091
10	18.7	3.0286	.1714	6.0286
**** E: 0				
*** C: 0				
** RR: 0				
* PP: 10				
30	14.3	31.6103	1.7426	5.6838
30	16.3	8.3448	.6759	4.9862
30	17.8	10.4641	1.4706	3.1111
30	21.9	37.7512	35.8537	.3317

Table N-1 (Cont.)

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SPK TIM	MEAS A-F	CO/SFC	HC/SFC	NOX/SFC
20	14.7	39.3250	2.0259	3.9187
20	16.5	7.9314	.6792	4.1447
20	18.3	9.0118	1.2604	2.3077
20	21.8	29.0762	21.8206	.6542
10	15.0	22.3089	1.0366	2.8063
10	16.4	5.7380	.3743	3.2032
10	18.8	6.5207	.5608	1.8571
10	20.8	11.5075	5.2609	.9436
* PP: 25				
30	14.5	21.8025	2.6543	12.9596
30	16.3	10.7683	1.2927	13.3293
30	18.1	12.2471	1.0353	6.7529
30	21.9	29.0000	16.3232	.8182
20	14.8	25.0682	1.6932	8.2386
20	16.6	9.5125	2.6375	14.0500
20	18.5	9.8921	2.1942	3.6354
20	21.3	24.8291	11.6496	1.1282
10	14.9	36.5842	1.2376	5.6040
10	19.5	6.3475	.3559	3.2288
* PP: 50				
30	15.1	60.0678	3.6610	22.2373
30	16.9	11.4483	1.6724	25.7586
30	18.7	12.0847	1.2034	15.8814
30	20.7	18.2540	5.3651	7.2698
20	15.3	47.8871	2.5968	17.3710
20	17.0	9.7258	.8226	18.4516
20	19.2	9.5970	.6567	9.0597
10	15.3	41.8169	1.3099	11.0563
10	17.2	6.7606	.4366	12.0282
** RR: 50				
* PP: 10				
30	15.4	13.2568	1.0608	2.7095
30	16.1	10.5123	2.0617	2.2840
30	17.6	16.3563	6.5517	1.2069
20	15.3	9.3085	1.0532	1.5160
20	16.2	7.8218	1.0402	1.8563
20	18.4	11.2974	2.5231	1.1179
10	15.3	1.9403	.1748	2.2184
10	16.5	5.1488	.2837	2.2093
* PP: 25				
30	15.9	10.7765	1.4941	4.0000
30	16.0	10.9610	1.2927	9.8049
30	18.2	13.1685	.9551	4.4157
30	20.7	35.0545	41.2455	.5455
20	15.2	12.9032	1.0215	3.8495

Table N-1 (Cont.)

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SPK TIM	MEAS A-F	CO/SFC	HC/SFC	NOX/SFC
20	16.4	10.0000	1.3765	5.4706
20	18.9	10.0102	.6939	3.1429
10	15.5	18.8273	.7455	3.4091
• PP: 50				
30	15.0	52.2167	3.2667	11.8500
30	16.8	11.9667	1.5500	13.8167
30	18.9	13.5484	1.3387	9.4839
20	15.4	31.5365	1.8462	9.3692
20	17.1	8.8254	.7143	11.7143
•• RH: 100				
• PP: 10				
30	15.9	34.1429	13.4439	.8010
30	15.8	24.0048	14.9324	.8454
30	17.0	28.7368	27.3349	.7512
30	21.6	39.0180	60.2535	.3239
20	16.0	22.6091	9.8893	.6087
20	18.3	12.8443	3.6085	.8726
20	18.2	18.9054	10.3973	.6210
20	20.7	27.8571	22.6494	.6277
10	15.9	8.5049	.7298	1.2702
10	16.5	5.7593	.5519	1.5145
10	18.7	6.4885	.6413	1.7040
10	19.7	11.4028	6.2201	1.0495
• PP: 25				
30	15.4	26.1963	8.9007	1.4206
30	16.4	10.8506	1.2874	4.3908
30	18.4	16.4187	2.0104	2.0833
30	20.2	34.6437	40.1351	.5405
20	15.6	13.2308	.9712	1.9712
20	16.6	25.9717	11.5700	1.2170
20	18.0	20.7563	9.4328	1.2353
20	21.2	29.7934	19.2645	.9587
10	16.4	10.6953	.5234	2.0703
10	19.5	8.5873	1.4286	2.8175
• PP: 50				
30	15.7	25.6719	2.1094	3.9687
30	17.1	14.3788	1.9697	5.5758
30	18.8	16.0212	2.1364	5.4091
30	20.8	24.3881	9.2985	3.7164
20	16.1	16.9583	1.1389	4.6389
20	17.5	9.7015	.8507	6.0896
20	19.8	10.4783	.8551	6.7391
10	15.8	18.6953	.6579	7.3026
10	17.7	6.0667	.4800	9.1600

Table N-1 (Cont.)

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SPK TIM	MEAS A-F	CO/SFC	HC/SFC	NOX/SFC
••• C: 1				
•• RH: 0				
• PP: 10				
30	14.3	2.4632	.3676	5.1397
30	16.1	2.2552	.1517	4.6966
30	17.8	2.4706	.2418	3.5229
30	21.9	3.9317	10.9659	.8293
20	14.7	2.2590	.4875	3.1375
20	16.5	2.3711	.1824	4.2704
20	18.3	2.8047	.2781	2.5858
20	21.8	3.9103	8.3563	.7390
10	15.0	2.1623	.2775	2.9215
10	16.4	2.3690	.1230	3.5187
10	18.8	6.5207	.1198	2.0000
10	20.8	3.1692	6.5026	1.1053
• PP: 25				
30	14.7	2.2469	.9136	12.0247
30	16.2	2.3373	.2651	12.8675
30	18.1	3.1059	.1765	6.7529
30	22.1	3.7629	3.4227	1.5876
20	14.8	2.4773	.3409	7.6077
20	16.6	2.4000	1.1500	13.0250
20	18.7	3.0316	.3895	3.0789
20	21.1	3.5763	3.1017	1.6695
10	14.7	2.5446	.2178	5.6436
10	19.5	2.9829	.1368	3.4957
• PP: 50				
30	15.1	2.7797	.7119	22.4007
30	17.0	2.7759	.3448	25.9828
30	18.5	2.8305	.4068	15.6102
30	20.6	3.1429	2.8254	7.6508
20	15.3	2.8387	.5484	17.3710
20	17.0	2.4516	.2258	17.9355
20	19.2	2.7612	.2687	9.2687
10	15.3	2.9718	.2458	11.4085
10	17.2	2.6197	.1408	11.6338
•• RH: 50				
• PP: 10				
30	15.4	2.6486	.3649	2.7005
30	16.2	2.2671	.6335	2.3002
30	17.6	2.7011	1.4138	1.6782
20	15.3	2.1217	.3333	1.5079
20	16.2	2.3333	.2586	2.0402
20	18.4	2.9744	.6308	1.4667
10	15.3	1.9003	.1748	2.2184
10	16.5	2.3814	.0930	2.4000

Table N-1 (Cont.)

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SPK TIM	MEAS A-F	CO/SFC	HC/SFC	NOX/SFC
• PP: 25				
30	15.8	2.2824	.4941	3.9862
30	16.0	2.2410	.2410	9.4458
30	18.1	3.1011	.1798	4.5006
30	20.9	3.7523	10.4587	.9459
20	15.2	2.5484	.1720	3.8367
20	16.4	2.3647	.4588	5.3882
20	18.9	3.0619	.2371	3.5258
10	15.5	2.6455	.1364	3.5909
10	19.4	8.5873	1.4286	2.8175
• PP: 50				
30	15.0	2.6000	.8167	12.0000
30	16.9	2.7333	.3333	13.8167
30	18.8	2.8710	.3710	10.0161
20	15.5	2.8000	.3692	9.3231
20	17.1	2.6508	.1905	11.7143
•• RH: 100				
• PP: 10				
30	15.0	3.4847	2.2245	.9184
30	16.1	3.7524	3.3398	.9854
30	17.0	2.8421	5.6269	.9091
30	21.8	3.9671	21.5869	.6526
20	15.9	2.4348	1.7866	.7273
20	16.3	2.5094	.7877	1.1226
20	18.2	2.9406	2.2877	.9689
20	20.7	3.8182	9.0649	.7835
10	15.9	2.2993	.2177	1.4556
10	16.5	2.3817	.1600	1.6390
10	18.7	2.9417	.1973	1.6475
10	19.7	3.3746	2.7067	1.0495
• PP: 25				
30	15.6	2.5421	1.5794	1.7944
30	16.4	2.3523	.2500	4.3750
30	18.4	3.1354	.3125	2.7812
30	20.2	3.6216	6.8919	1.0721
20	15.6	2.6058	.2115	2.2596
20	16.6	3.0283	1.6887	1.2736
20	18.9	3.0750	1.4833	1.7750
20	21.2	3.6198	4.4959	1.2810
10	16.5	2.8359	.1250	2.2031
10	19.6	3.1667	.2460	2.8175
• PP: 50				
30	15.7	2.7187	.5156	4.3906
30	17.0	2.7463	.3881	6.0149

Table N-1 (Cont.)

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SPK TIM	MEAS A-F	CO/SFC	HC/SFC	NOX/SFC
30	18.6	3.0152	.6818	6.0909
30	20.9	3.4030	2.9254	5.2537
20	16.0	2.8889	.2917	4.8611
20	17.5	2.6866	.2388	6.2239
20	19.6	3.1739	.2890	6.9275
10	15.8	2.7237	.1711	7.4868
10	17.7	2.7067	.1333	9.1600

Appendix O

ENGINE TEST DATA – EMISSIONS VS. AIR-FUEL RATIO

This appendix contains a series of tables showing the relationship between emissions and air-fuel ratio. Following are definitions of pertinent abbreviations and column headings:

E	Engine
C	Catalyst
RR	Exhaust recirculation rate
PP	Percent power
ST	Advance (°BTC)
MEAS AFR	Measured air-fuel ratio
CO	CO emission (g/bhp-hr)
HC	HC emission (g/bhp-hr)
NOX	NO_x emission (g/bhp-hr)
RANK NO.	Total weighted emissions (CO/3.4) + (HC/0.41) + (NO_x/0.40) (g/bhp-hr) /(g /mi)

Table O-1

ENGINE TEST DATA, SHOWING RELATIONSHIP BETWEEN EMISSIONS AND AIR-FUEL RATIO– 1,200 RPM, ENGINE A

```
PAGE 1
DATE: 12/6 11:12
DATA BASE: /3.0 E1200/
REPORT FORM: /3.0 RPT2/

  MEAS
  AFR          CO         HC         NOX  RANK NO

••••• E: A
 •••• C: 0
  ••• RP:   0
   •• PP: 10
    • ST: 10

  14.1      62.76       2.94        2.53  31.9546
  15.8      13.61       1.22        2.25  12.6036
  17.5      16.00       3.29        1.74  17.0803
  18.9      28.77      17.41        1.20  53.9252

    • ST: 20

  14.4      38.27       3.91        2.41  26.8175
  15.8      15.46       2.32        2.35  16.0806
  17.2      18.34       5.17        1.38  21.4539
  19.2      31.45      25.93         .89  74.7189

    • ST: 30

  14.9      47.56       6.03        2.88  35.8956
  16.3      16.17       4.37        3.40  23.9144
  17.9      19.58       9.69        1.94  34.3680
  19.8      29.69      49.68        1.43 133.4781

   •• PP: 25
    • ST: 10

  14.5      46.53       1.79        3.28  26.2511
  15.9      10.14        .96        3.23  13.3988
  16.7       8.48        .81        2.87  11.6447
  19.1      14.29       6.02        1.16  21.7859

    • ST: 20

  14.5      18.35       1.97        3.62  19.2519
  16.2       7.18       1.21        3.30  13.3130
  17.3       8.81       1.54        3.25  14.4723
  19.4      13.64       8.62        1.21  28.0612

    • ST: 30

  14.4      24.90       2.76        5.58  28.0052
  16.0       6.95       1.84        5.03  19.1069
  17.5       8.84       2.28        2.35  14.0360
  19.6      13.74      14.70        1.28  43.0948

   •• PP: 50
    • ST: 10
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Table O-1 (Cont.)

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  MEAS
  AFR          CO         HC         NOX  RANK NO

  14.6      51.05       1.47        4.61  30.1251
  15.2      16.78       1.10        2.38  13.5682
  16.2       7.03        .75        5.66  18.0469
  17.6       7.10       1.04        5.53  18.4498

    • ST: 20

  14.6      41.98       2.10        6.52  33.7690
  16.4       6.81       1.44        7.78  24.9651
  17.9       5.64       1.18        5.20  17.5369
  19.7      12.30      11.17        5.66  45.0115

    • ST: 30

  14.8      52.27       2.44        8.71  43.0997
  16.4       4.94       1.91       11.35  34.4865
  18.1       5.14       1.68        7.86  25.2593
  20.2       9.73      10.70        5.15  41.8343

   •• PP: 90
    • ST: 10

  14.5      53.90       1.41        8.92  41.5920
  15.7      23.80       1.16        7.89  29.0543
  16.3       9.35        .93        8.62  26.5683

    • ST: 20

  14.7      66.63       1.93        8.58  45.7544
  15.9      39.45       1.87        9.20  39.1639
  16.9      10.96       1.43       11.31  34.9863

    • ST: 30

  14.9      49.76       2.16       12.91  52.1786
  15.1      54.81       2.24       11.48  50.2840

  ••• RR:  50
   •• PP: 10
    • ST: 10

  14.9      15.99       1.18        2.07  12.7560
  16.2      23.86       9.26        1.54  33.4530
  17.4      29.17      19.82        2.31  62.6959
  19.0      39.07      32.21        1.10  92.8022

    • ST: 20

  15.3      19.11       4.24        1.32  19.2621
  16.0      23.10       8.18        1.29  29.9703
  17.3      25.76      31.00        1.37  88.6112
  18.6      31.48      38.17        1.14 105.2064
```

Table O-1 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
• ST: 30				
15.1	23.19	7.42	1.49	28.6431
16.3	17.80	6.73	1.87	26.3249
17.4	26.85	26.04	3.03	78.9843
19.6	39.01	78.62	1.58	207.1796
•• PP: 25				
• ST: 10				
15.0	29.69	1.99	1.66	17.7360
15.7	9.68	1.46	1.46	10.0580
16.5	9.49	1.47	1.95	11.2515
• ST: 20				
14.6	13.25	1.55	1.91	12.4525
16.0	7.86	1.26	2.04	10.4849
17.6	11.42	2.72	2.37	15.9180
19.0	16.33	13.86	.92	40.9078
• ST: 30				
14.3	24.32	2.49	2.11	18.5011
16.2	8.61	2.31	2.41	14.1916
17.3	12.00	6.93	1.31	23.7069
19.8	16.18	32.52	.76	85.9700
•• PP: 50				
• ST: 10				
13.9	81.45	1.89	1.99	33.5406
15.0	22.20	1.14	1.46	12.9594
• ST: 20				
15.1	15.70	1.66	3.75	18.0414
15.9	5.88	1.45	2.93	12.5910
• ST: 30				
15.0	33.85	2.24	3.67	24.5943
16.2	4.67	1.79	6.33	21.5644
18.1	5.84	2.39	4.61	19.0719
•• PP: 90				
• ST: 30				
15.3	41.63	2.11	8.53	38.7155
15.4	42.46	2.09	7.76	36.9858
••• BR: 100				
•• PP: 10				

Table O-1 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
• ST: 10				
14.5	40.18	14.32	1.15	49.6136
14.7	182.60	84.68	1.87	264.9175
16.2	53.80	60.40	1.72	167.4406
18.2	44.17	32.58	1.11	95.2296
• ST: 20				
14.5	41.71	34.16	1.36	98.9847
14.8	78.25	51.41	1.46	152.0549
17.0	38.38	41.27	1.25	115.0718
18.7	49.04	101.42	1.26	264.9394
• ST: 30				
14.3	79.95	35.74	1.17	113.6104
15.4	119.50	71.90	1.87	215.1879
15.6	55.41	137.83	3.16	360.3678
17.4	39.67	95.09	1.13	246.4195
•• PP: 25				
• ST: 10				
14.9	21.16	5.27	1.33	22.4022
15.2	28.60	14.15	1.03	45.4900
16.3	14.24	4.94	1.64	20.3370
18.4	26.18	16.30	1.08	50.1561
• ST: 20				
14.8	23.40	4.80	.78	20.5397
16.1	13.30	3.08	1.14	14.2740
17.0	16.75	10.11	2.26	35.2350
19.1	20.82	30.04	1.00	81.8918
• ST: 30				
14.8	21.18	5.16	.95	21.1602
15.6	16.93	13.51	1.23	41.0056
16.9	16.20	26.00	.93	70.5043
19.4	18.71	37.91	.87	148.9218
•• PP: 50				
• ST: 10				
14.9	38.50	1.24	1.15	17.2229
15.0	28.27	1.68	2.28	18.1123
16.1	8.10	.87	4.01	14.5293
17.4	6.68	1.30	5.70	19.3854
• ST: 20				

Table O-1 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
15.1	29.69	2.63	1.16	18.0470
15.6	22.80	5.61	1.06	23.0388
17.8	8.16	3.44	2.73	17.6152
19.6	11.46	7.37	5.46	34.9962
* ST: 30				
15.1	16.16	2.87	1.69	15.9779
16.2	8.36	2.91	2.79	16.5314
18.0	7.60	1.96	3.02	14.5658
20.4	10.11	16.67	5.63	57.7071
** PP: 90				
* ST: 10				
15.2	47.03	1.24	7.89	36.5817
15.4	19.93	.98	7.28	26.4520
15.9	18.03	.95	8.04	27.7200
* ST: 20				
15.7	26.31	1.39	5.68	25.3285
16.1	14.92	1.49	8.69	29.7474
17.1	8.09	1.37	8.34	26.5709
* ST: 30				
15.8	7.34	1.82	6.56	22.9478
15.8	9.51	1.94	6.50	23.7780
**** C: 1				
*** RR: 0				
** PP: 10				
* ST: 10				
10.7	3.32	1.74	.68	6.9204
14.1	3.77	.96	2.06	8.6003
15.8	4.34	.47	2.38	8.3728
17.5	4.98	.86	1.49	7.2873
* ST: 20				
14.4	3.61	1.16	2.01	8.9160
15.8	3.89	.85	2.45	9.3423
17.2	4.52	2.11	1.38	9.9258
19.2	5.40	5.34	1.27	17.7876
* ST: 30				
14.9	6.56	2.29	2.28	13.2146
16.3	3.93	1.47	2.87	11.9162
17.9	4.11	2.63	2.08	12.8235
19.8	4.80	7.78	1.67	24.5624

Table O-1 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
** PP: 25				
* ST: 10				
14.5	1.99	.39	2.78	8.4865
15.9	1.94	.40	2.98	8.9062
16.7	2.42	.25	2.69	8.0465
19.1	2.91	1.53	1.74	8.9376
* ST: 20				
14.7	1.84	.52	3.02	9.3595
16.2	1.89	.34	3.11	9.1602
17.3	2.40	.12	3.14	8.8486
19.4	2.71	2.30	1.53	10.2318
* ST: 30				
14.4	1.76	.60	4.79	13.9561
16.0	2.02	.46	4.76	13.6161
17.5	2.18	.55	2.15	7.3576
19.8	2.63	2.04	1.48	9.4491
** PP: 50				
* ST: 10				
14.6	1.53	.34	4.61	12.8043
15.2	1.54	.30	2.25	6.8496
16.2	1.66	.19	5.24	14.0516
17.6	1.73	.34	5.27	14.5131
* ST: 20				
14.6	1.34	.45	6.15	16.8667
16.4	1.45	.34	7.31	19.5307
17.9	1.47	.27	4.82	13.1409
19.7	1.86	1.54	6.12	19.6032
* ST: 30				
14.8	1.38	.46	8.71	23.3028
16.4	1.33	.41	10.82	28.4412
18.1	1.48	.33	7.20	19.2402
20.2	1.80	1.76	4.98	17.2721
** PP: 90				
* ST: 10				
14.5	1.46	.29	8.92	23.4367
15.6	1.52	.27	7.41	19.6306
16.3	1.64	.24	8.16	21.4677
* ST: 20				

Table O-1 (Cont.)

PAGE 7 12/6

MEAS AFR	CO	HC	NOX	RANK NO
14.7	1.54	.42	8.59	22.9523
15.9	1.65	.43	8.95	23.9091
~~16.8~~	~~1.53~~	~~.33~~	~~10.55~~	~~27.6299~~
+ ST: 30				
14.9	1.37	.51	12.74	33.4968
15.1	1.44	.51	12.32	32.4674
+++ RR: 50				
++ PP: 10				
+ ST: 10				
10.8	3.58	3.22	.71	10.6816
~~14.9~~	~~4.03~~	~~.49~~	~~1.65~~	~~6.5054~~
16.2	5.30	3.08	1.79	13.5460
17.4	7.21	4.17	2.89	19.5163
+ ST: 20				
~~15.1~~	~~4.23~~	~~1.41~~	~~1.13~~	~~7.5081~~
16.0	4.46	2.40	1.29	10.3904
17.3	5.15	6.19	1.60	20.6123
~~18.6~~	~~5.40~~	~~6.87~~	~~1.14~~	~~21.1943~~
+ ST: 30				
15.1	3.75	2.25	1.49	10.3157
16.3	3.63	2.37	1.87	11.5231
~~17.4~~	~~4.34~~	~~5.47~~	~~3.46~~	~~23.2679~~
19.6	5.46	15.10	1.85	43.0602
++ PP: 25				
+ ST: 10				
~~15.0~~	~~2.28~~	~~.90~~	~~1.65~~	~~6.9007~~
15.7	2.22	.41	1.58	5.6029
16.5	2.52	.31	1.95	6.3723
+ ST: 20				
~~14.6~~	~~1.92~~	~~.43~~	~~1.53~~	~~5.4385~~
16.0	2.07	.29	1.85	5.9411
17.5	2.67	.62	2.53	8.6225
~~19.0~~	~~2.84~~	~~2.77~~	~~1.18~~	~~10.4826~~
+ ST: 30				
14.3	1.73	.56	1.79	6.3497
16.2	2.21	.56	2.36	7.9159
~~17.3~~	~~2.40~~	~~1.58~~	~~1.42~~	~~8.1095~~
19.8	2.71	6.78	1.02	19.8836

Table O-1 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
++ PP: 50				
+ ST: 10				
13.7	1.47	.29	1.99	6.1147
15.0	1.69	.31	1.28	4.4267
+ ST: 20				
~~15.1~~	~~1.40~~	~~.39~~	~~3.23~~	~~9.4380~~
15.9	1.47	.33	2.76	8.1372
+ ST: 30				
15.0	1.26	.47	3.43	10.0919
~~16.2~~	~~1.34~~	~~.34~~	~~5.80~~	~~15.7234~~
18.1	1.52	.45	4.19	12.0196
++ PP: 90				
+ ST: 30				
~~15.4~~	~~1.43~~	~~.48~~	~~8.54~~	~~22.9413~~
15.4	1.36	.44	7.31	19.7482
+++ RR: 100				
++ PP: 10				
+ ST: 10				
10.3	3.73	4.56	.72	14.0190
14.5	5.14	1.62	1.54	9.3130
~~14.7~~	~~25.89~~	~~18.83~~	~~1.41~~	~~57.0636~~
16.2	6.49	7.93	1.88	25.9503
+ ST: 20				
14.4	5.11	6.61	1.36	21.0249
~~14.8~~	~~6.83~~	~~10.14~~	~~1.19~~	~~29.4905~~
17.0	5.62	6.98	1.50	22.4273
18.7	6.33	18.53	1.26	50.2069
+ ST: 30				
~~14.3~~	~~4.15~~	~~8.34~~	~~1.17~~	~~19.6090~~
15.4	5.30	19.90	1.20	53.0954
15.6	5.93	22.22	3.29	64.1642
~~17.4~~	~~5.19~~	~~15.86~~	~~1.63~~	~~44.2844~~
++ PP: 25				
+ ST: 10				
14.9	2.75	2.40	1.33	9.9875
~~15.2~~	~~3.58~~	~~2.12~~	~~1.18~~	~~9.1737~~
16.3	2.83	.74	1.64	6.7372
18.4	3.11	2.79	1.39	11.1946

Table O-1 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
• ST: 20				
14.8	2.36	.83	.89	4.9435
16.1	2.29	.55	1.25	5.1400
17.0	2.99	1.87	2.26	11.0904
19.1	3.21	5.80	1.14	17.9405
• ST: 30				
14.8	2.03	.86	.86	4.8446
15.6	2.53	1.93	1.23	8.5264
16.9	2.56	4.64	1.17	14.9950
19.4	3.29	12.12	1.17	33.4536
•• PP: 30				
• ST: 10				
14.9	1.65	.29	1.31	4.4676
15.0	1.95	.46	2.11	6.9705
16.1	1.71	.16	3.85	10.5182
17.4	1.74	.31	5.49	14.9929
• ST: 20				
15.1	1.55	.46	1.31	4.8528
15.6	1.91	.84	1.27	5.7855
17.8	1.76	.62	2.73	8.8348
19.6	2.01	1.28	5.74	18.0631
• ST: 30				
15.1	1.44	.51	1.65	5.7924
16.2	1.44	.45	2.72	8.3211
18.0	1.60	.96	3.03	10.3871
20.4	1.85	2.22	5.86	20.6088
•• PP: 90				
• ST: 10				
15.2	1.59	.39	7.46	20.0689
15.4	1.57	.24	7.11	18.8221
15.9	1.79	.24	7.90	20.8618
• ST: 20				
15.7	1.47	.35	5.49	15.0110
16.1	1.52	.38	8.38	22.3239
17.1	1.55	.32	8.08	21.4364
• ST: 30				
15.8	1.43	.47	6.13	16.8919
15.8	1.40	.43	6.33	17.2855

Table O-2

ENGINE TEST DATA, SHOWING RELATIONSHIP BETWEEN EMISSIONS AND AIR-FUEL RATIO – 1,200 RPM, ENGINE B

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MEAS AFR	CO	HC	NOX	RANK NO
***** E: B				
**** C: 0				
*** RP: 0				
** PP: 10				
* ST: 10				
14.4	49.82	3.82	2.88	31.1700
16.4	20.17	3.25	2.42	19.9092
18.5	31.89	19.59	1.50	60.9099
20.0	63.47	73.30	1.42	200.9981
* ST: 20				
14.7	75.93	9.16	2.83	51.7488
16.4	23.04	5.28	2.57	26.0795
18.6	33.80	33.95	1.27	95.9211
20.9	60.21	105.68	1.06	278.1149
* ST: 30				
14.3	59.44	11.15	3.09	52.2848
16.1	22.27	15.48	2.97	51.7311
18.2	29.83	23.15	1.68	69.4369
19.6	45.09	94.45	1.79	248.0538
** PP: 25				
* ST: 10				
14.6	56.24	2.60	2.74	29.7326
16.2	10.32	1.02	2.51	11.7981
17.3	10.82	.87	1.45	8.9293
19.7	17.90	4.86	1.08	19.8184
* ST: 20				
14.6	32.41	3.07	3.00	24.3202
16.4	9.99	2.07	2.55	14.3620
17.9	13.17	4.71	1.63	19.4363
20.3	21.85	13.45	.72	41.0313
* ST: 30				
14.4	25.39	3.77	3.94	26.5128
16.6	9.92	2.71	3.00	17.0274
18.5	13.75	10.20	1.88	33.6222
20.6	21.76	26.44	.94	73.2378
** PP: 50				
* ST: 10				
14.6	21.96	1.72	4.44	21.7539
15.9	6.16	.69	4.36	14.3947
17.3	6.93	.75	2.82	10.9175

Table O-2 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
19.0	8.97	1.19	1.47	9.2157
* ST: 20				
14.3	23.81	2.28	5.80	27.0639
15.8	5.85	1.49	5.74	19.4852
17.8	7.27	1.44	2.60	12.1504
19.5	11.19	4.72	.94	17.1534
* ST: 30				
14.5	29.77	3.33	9.56	40.7778
16.2	5.40	2.00	7.69	25.6913
18.5	6.29	2.09	3.06	14.5976
20.6	10.08	9.01	.95	27.3153
** PP: 90				
* ST: 10				
14.7	19.26	1.73	7.80	29.5842
17.5	5.47	.57	4.71	14.7741
22.7	4.68	.81	8.44	24.4521
* ST: 20				
14.6	11.53	2.05	10.77	35.3162
16.2	4.44	1.43	12.16	35.1937
17.5	5.24	1.43	7.59	24.0040
18.4	5.88	1.12	3.25	12.5861
* ST: 30				
14.7	9.12	2.08	13.66	41.9955
16.0	3.67	1.83	18.31	51.3178
17.6	3.85	1.52	11.04	32.4397
19.3	4.79	1.57	4.33	16.0631
*** RP: 50				
** PP: 10				
* ST: 10				
14.7	31.65	3.86	2.05	23.8485
16.4	24.31	8.43	1.89	32.4360
18.6	42.48	40.17	1.20	113.4697
19.9	87.49	133.89	1.57	356.2183
* ST: 20				
15.0	22.51	4.07	2.25	22.1724
16.8	26.58	19.98	1.94	37.2530
18.0	40.34	56.88	1.16	153.4984
20.3	67.16	122.92	1.29	322.7828

Table O-2 (Cont.)

PAGE 12 12/6

MEAS AFR	CO	HC	NOX	RANK NO
* ST: 30				
14.7	29.78	17.44	2.04	56.3954
16.2	27.94	23.04	2.14	69.7628
17.3	42.47	69.75	1.93	187.4381
19.7	49.39	124.03	1.87	321.7137
** PP: 25				
* ST: 10				
15.0	14.29	1.26	1.56	11.1761
16.2	10.72	1.01	1.75	9.9914
17.3	12.09	1.31	1.24	9.8510
19.6	26.65	23.13	.86	66.4029
* ST: 20				
15.3	14.29	2.44	1.64	14.2547
16.5	11.65	2.64	1.83	14.4405
18.1	15.96	6.59	.98	23.2173
19.8	28.17	27.25	.78	76.0987
* ST: 30				
14.8	12.68	3.14	2.55	17.7629
16.3	12.62	6.17	1.42	22.3105
18.7	16.02	12.13	1.81	38.3221
** PP: 50				
* ST: 10				
15.2	8.01	1.06	2.77	11.8662
15.9	6.56	.66	2.67	10.2142
* ST: 20				
14.9	6.31	1.70	1.95	10.8772
15.7	6.23	1.44	2.86	12.4945
20.4	9.67	1.98	1.42	11.2234
* ST: 30				
14.4	11.19	2.36	3.63	18.0958
16.7	5.90	2.10	2.85	13.9822
18.4	7.38	2.62	2.39	14.5558
** PP: 90				
* ST: 10				
14.9	17.06	1.47	4.39	19.5780
16.5	5.75	.85	6.00	18.7843
* ST: 20				

Table O-2 (Cont.)

PAGE 13 12/6

MEAS AFR	CO	HC	NOX	RANK NO
14.5	11.94	1.71	5.44	21.2825
15.9	4.30	1.32	5.83	19.0592
17.0	5.13	1.19	4.74	15.7613
* ST: 30				
14.7	9.64	2.10	6.26	23.6972
16.1	3.60	1.73	9.01	27.8033
17.5	4.29	1.46	6.84	21.8963
*** PP: 100				
** PP: 10				
* ST: 10				
14.9	51.55	23.72	1.48	76.7154
16.4	45.91	25.23	1.57	78.9645
18.2	46.01	42.15	1.22	114.3872
19.9	87.49	133.89	1.57	356.2183
* ST: 20				
14.9	41.12	21.65	1.54	68.7490
15.9	53.63	53.24	2.13	150.9522
18.2	56.23	94.03	1.14	248.7297
20.4	77.27	181.80	1.35	469.5161
* ST: 30				
13.5	176.98	69.00	1.48	224.0456
15.1	56.85	72.97	2.02	190.7462
16.1	55.00	104.64	1.74	275.7460
19.0	54.76	143.08	1.43	368.6565
** PP: 25				
* ST: 10				
14.9	15.15	2.86	1.27	14.6065
16.2	14.54	2.29	1.22	12.9118
17.3	22.55	7.97	.79	28.0464
17.9	33.08	31.12	.86	87.7819
* ST: 20				
15.2	21.36	7.56	.94	27.0714
16.0	20.85	4.76	.90	32.4122
17.8	22.84	16.40	.91	48.9026
19.0	29.64	42.91	.68	115.0762
* ST: 30				
14.9	16.74	6.73	1.32	24.6382
15.7	23.00	24.57	.92	68.9915
18.7	20.86	22.15	1.25	63.2847

Table O-2 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
20.0	25.28	49.91	1.00	131.6670
** PP: 50				
* ST: 10				
15.7	8.30	.89	1.29	7.8369
16.4	7.42	.78	1.59	8.0598
17.5	7.72	.75	1.96	8.9009
18.9	8.90	1.11	1.44	8.9250
* ST: 20				
14.7	15.99	7.61	8.75	45.1389
15.9	10.01	2.75	1.07	12.3264
17.5	14.67	8.20	.84	26.4147
19.6	14.56	10.82	.56	32.0726
* ST: 30				
15.9	8.08	3.27	1.02	12.9021
16.9	11.47	9.55	1.07	29.3412
18.4	11.75	9.49	1.13	29.4272
20.4	13.18	20.70	.69	56.0893
** PP: 90				
* ST: 10				
15.2	8.49	1.18	2.65	12.0001
15.9	5.24	.84	3.43	12.1650
17.4	5.48	.55	4.39	13.9282
* ST: 20				
14.8	13.25	1.64	1.78	12.3471
15.9	5.98	1.44	2.60	11.7710
17.1	6.54	1.68	2.22	11.5711
18.8	6.43	1.48	2.64	12.1019
* ST: 30				
14.8	4.24	1.79	1.98	10.5629
15.9	4.15	1.69	3.98	15.2925
17.8	5.28	1.69	3.96	15.5749
19.0	5.75	2.09	2.80	13.7887
**** C: 1				
*** RP: 0				
** PP: 10				
* ST: 10				
14.4	5.19	1.67	2.19	11.0746
16.4	5.74	1.46	2.16	10.6492
18.5	7.31	3.52	1.50	14.4854

Table O-2 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
20.0	8.15	16.50	1.42	46.1910
* ST: 20				
14.7	4.15	3.05	2.34	14.5096
16.4	5.55	2.53	2.22	13.3531
18.6	5.66	5.52	1.97	20.0531
20.9	7.13	15.38	1.60	43.6093
* ST: 30				
14.3	4.23	2.96	2.51	14.7386
16.1	4.70	5.18	2.37	19.9415
18.2	5.41	7.38	1.92	24.3912
19.6	6.56	17.12	2.39	49.6605
** PP: 25				
* ST: 10				
14.6	2.70	.74	2.33	8.4240
16.2	2.91	.36	2.20	7.2339
17.5	3.25	.31	1.44	5.3120
19.7	3.93	.95	1.26	6.6230
* ST: 20				
14.6	2.25	.69	2.40	8.3447
16.4	2.43	.57	2.22	7.6549
17.9	2.86	1.26	1.56	7.8143
20.3	3.40	2.60	.96	9.7415
* ST: 30				
14.4	1.90	.87	3.12	10.4808
16.6	2.35	.65	2.63	8.8515
18.5	2.52	1.97	1.80	10.2461
20.6	3.15	2.98	1.33	11.5198
** PP: 50				
* ST: 10				
14.6	1.70	.39	3.96	11.3512
15.9	1.85	.17	3.95	10.8338
17.3	2.08	.22	2.59	7.6234
19.0	2.28	.41	1.59	5.6456
* ST: 20				
14.3	1.57	.46	5.04	14.1837
15.8	1.60	.32	5.02	13.8187
17.8	1.92	.35	2.47	7.5934
19.5	2.10	.91	1.25	5.9622

Table O-2 (Cont.)

PAGE 16 12/6

MEAS AFR	CO	HC	NOX	RANK NO
• ST: 30				
~~14.4~~	~~1.47~~	~~.39~~	~~6.22~~	~~17.4214~~
16.2	1.61	.42	7.01	19.0229
18.5	1.66	.44	2.89	8.7864
~~20.6~~	~~2.06~~	~~1.14~~	~~1.40~~	~~6.8864~~
•• PP: 90				
~~• ST: 10~~				
14.7	1.16	.35	7.36	19.5948
~~16.3~~	~~1.20~~	~~.21~~	~~8.01~~	~~20.9078~~
17.5	1.63	.16	4.53	12.1947
~~• ST: 20~~				
14.6	1.28	.40	10.11	26.6271
~~16.1~~	~~1.37~~	~~.27~~	~~11.61~~	~~30.0865~~
17.5	1.37	.54	7.59	20.6950
18.4	1.57	.23	3.22	9.0727
• ST: 30				
~~14.7~~	~~1.15~~	~~.43~~	~~12.88~~	~~35.5370~~
16.0	1.27	.34	17.47	44.8778
17.7	1.26	.28	9.89	25.7785
~~14.3~~	~~1.40~~	~~.30~~	~~4.00~~	~~11.1435~~
••• RP: 50				
~~•• PP: 10~~				
• ST: 10				
~~14.7~~	~~5.61~~	~~1.50~~	~~1.54~~	~~9.1585~~
16.4	6.39	2.19	1.60	11.2209
18.6	7.50	5.67	1.20	19.0352
~~19.9~~	~~9.58~~	~~25.18~~	~~1.57~~	~~68.1573~~
• ST: 20				
15.0	4.53	1.63	1.80	9.8080
16.8	5.91	3.94	1.94	16.1980
~~18.0~~	~~5.84~~	~~8.40~~	~~1.74~~	~~26.5555~~
20.1	7.85	25.28	1.66	68.1174
~~• ST: 30~~				
14.7	4.44	4.26	1.72	15.9461
~~16.2~~	~~5.48~~	~~6.10~~	~~1.91~~	~~21.2648~~
17.3	6.55	19.12	2.62	55.1106
19.7	7.04	26.36	2.19	71.8383
•• PP: 25				
• ST: 10				

Table O-2 (Cont.)

PAGE 17 12/6

MEAS AFR	CO	HC	NOX	RANK NO
14.9	2.94	.45	1.37	5.3873
16.0	3.03	.30	1.68	5.8229
~~17.3~~	~~3.49~~	~~.42~~	~~1.24~~	~~5.1509~~
19.6	4.33	7.11	1.25	21.7400
• ST: 20				
15.3	2.57	.62	1.47	5.9431
~~16.5~~	~~2.75~~	~~.62~~	~~1.71~~	~~6.5960~~
18.1	3.16	1.22	1.12	6.7050
19.8	3.92	5.77	1.04	17.8261
• ST: 30				
~~14.8~~	~~2.05~~	~~.71~~	~~2.04~~	~~7.4348~~
16.3	2.50	1.30	1.37	7.3310
18.7	2.78	2.26	1.54	10.1798
•• PP: 50				
• ST: 10				
15.2	1.89	.26	2.43	7.2650
15.9	1.98	.17	2.98	8.4470
• ST: 20				
~~14.9~~	~~1.69~~	~~.36~~	~~1.84~~	~~5.9751~~
15.7	1.70	.29	2.67	7.8823
20.0	2.34	.47	1.52	5.6346
• ST: 30				
~~14.4~~	~~1.47~~	~~.49~~	~~3.30~~	~~9.8775~~
16.7	1.78	.42	2.67	8.2229
18.4	1.71	.54	2.39	7.7950
•• PP: 90				
• ST: 10				
14.9	1.30	.31	4.26	11.7885
16.5	1.36	.20	5.80	15.3878
• ST: 20				
~~14.5~~	~~1.08~~	~~.34~~	~~4.81~~	~~13.1719~~
15.9	1.28	.25	5.72	15.2862
17.0	1.30	.28	4.15	11.4403
• ST: 30				
~~14.7~~	~~1.17~~	~~.44~~	~~5.31~~	~~14.6923~~
16.0	1.20	.32	8.61	22.6584
17.5	1.31	.28	6.27	16.7432

Table O-2 (Cont.)

PAGE 18 12/6

MEAS AFR	CO	HC	NOX	RANK NO
••• RR: 100				
•• PP: 10				
• ST: 10				
14.9	7.40	3.56	1.97	15.7844
16.4	7.86	4.42	1.57	17.0173
18.2	7.88	5.59	1.58	19.9018
19.9	9.58	25.18	1.57	68.1573
• ST: 20				
14.9	5.47	5.03	1.54	17.7271
15.9	7.43	11.02	2.44	35.1633
18.2	6.54	13.23	1.47	37.8668
20.2	8.73	33.83	1.36	84.4798
• ST: 30				
13.5	5.56	11.89	1.48	34.3353
15.1	6.15	15.22	2.02	43.9808
16.1	6.89	20.10	2.03	50.1259
19.0	7.15	33.47	1.91	88.5121
•• PP: 25				
• ST: 10				
14.9	3.67	.72	1.27	6.0105
16.2	3.52	.48	1.22	5.2560
16.8	4.04	5.51	.81	16.6523
17.3	4.08	1.27	1.15	7.1726
• ST: 20				
15.2	3.04	1.38	.95	6.6350
16.0	3.17	1.27	1.13	6.8549
17.8	3.41	2.87	.91	10.2779
19.9	3.83	8.18	1.02	23.6277
• ST: 30				
14.9	2.30	1.31	1.26	7.0216
15.7	2.89	2.62	1.05	9.8652
18.7	3.13	3.32	1.54	12.8681
20.0	3.37	7.57	1.34	22.8046
•• PP: 50				
• ST: 10				
15.7	2.32	.25	1.45	4.9171
16.4	2.23	.18	1.58	5.0449
17.5	2.32	.21	1.96	6.0945
19.0	2.31	.36	1.61	5.5825

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MEAS AFR	CO	HC	NOX	RANK NO
• ST: 20				
14.7	2.31	1.14	.97	5.8849
15.9	2.01	.51	1.25	4.9601
17.5	2.42	1.14	1.05	6.1173
19.6	2.39	1.59	.90	6.8310
• ST: 30				
14.9	1.77	.64	1.02	4.6316
16.0	2.07	1.21	1.25	6.6850
18.4	2.04	1.33	1.38	7.2939
20.4	2.44	4.14	1.03	13.3902
•• PP: 90				
• ST: 10				
15.2	1.49	.29	2.72	7.9456
15.9	1.40	.19	3.43	9.4502
17.4	1.66	.14	4.16	11.2297
• ST: 20				
14.8	1.35	.32	1.78	5.6275
15.9	1.58	.25	2.67	7.7495
17.1	1.53	.39	2.29	7.1262
18.8	1.65	.27	2.84	7.7438
• ST: 30				
14.8	1.28	.38	1.93	6.1283
15.9	1.36	.29	3.86	10.7573
17.8	1.59	.29	3.96	11.9485
19.0	1.53	.39	2.73	8.2262

Table O-3

ENGINE TEST DATA, SHOWING RELATIONSHIP BETWEEN EMISSIONS AND AIR-FUEL RATIO – 1,600 RPM, ENGINE A

```
 'PAGE 1
 DATE: 12/6 11:46
 DATA BASE: /3.0 E1600/
 REPORT FORM: /3.0 RPT2/

   MEAS
   AFR         CO         HC        NOX  RANK NO

 ***** E: A
  **** C: 0
   *** RR:   0
    ** PP: 10
     * ST: 10

   14.8     43.50       1.48       4.09  26.6289
   16.2     13.39       1.09       3.88  16.2968
   17.4     18.38       3.27       3.62  22.4315
   20.0     37.05      27.55       1.58  82.0422

     * ST: 20

   15.0     58.05       3.38       4.08  35.5174
   16.5     16.09       1.87       3.68  18.4933
   18.4     26.76      16.02       2.24  52.5438
   19.9     46.42      48.24       1.12 134.1115

     * ST: 30

   14.4     48.23       3.24       3.59  31.0627
   16.2     18.80       7.18       4.63  34.6166
   18.5     30.05      24.14       4.01  77.7413
   19.8     45.33      65.58       3.09 181.0086

    ** PP: 25
     * ST: 10

   13.6     29.80       1.13       3.10  19.2708
   15.6      7.63        .30       3.38  11.4258
   16.9      8.05        .57       2.65  10.3829
   17.8      9.80       1.96       1.95  12.5378

     * ST: 20

   13.7     29.79       1.79       3.26  21.2776
   16.2      8.53        .89       4.05  14.8046
   18.6     12.66       2.50       1.66  13.9711
   21.1     30.14      25.30        .73  72.3970

     * ST: 30

   13.7     30.87       2.69       3.85  25.2654
   17.4      9.91       1.43       3.17  14.3275
   20.8     14.93       3.78       2.16  19.0197

    ** PP: 50
     * ST: 10

   14.7     30.44       1.78       4.82  25.3444
```

Table O-3 (Cont.)

```
 'PAGE 2 12/6

   MEAS
   AFR         CO         HC        NOX  RANK NO

   15.5     15.28       1.20       6.55  23.7959
   16.5      7.01        .57       4.73  15.2770
   17.3      5.93        .41       4.54  14.2191

     * ST: 20

   14.8     19.44       2.35       6.91  28.7244
   16.5      6.66       1.26       8.17  25.4570
   18.1      7.78        .85       4.52  15.0014
   19.4     12.92       3.67       2.13  18.0762

     * ST: 30

   14.8     17.70       2.57       9.85  36.0992
   16.1      5.66       1.85      10.54  32.5269
   17.5      6.70       1.50       7.50  24.3791
   20.1     10.86       5.51       1.97  21.5581

    ** PP: 90
     * ST: 10

   15.0     37.48       1.30       8.96  36.5943
   16.1     10.85        .60      10.61  31.1796

     * ST: 20

   14.9     44.85       1.64      11.33  45.5103
   16.1      9.00       1.11      14.66  42.0044
   17.3      5.24        .87      13.09  36.3881

     * ST: 30

   14.9     35.17       1.99      15.57  54.1228
   16.4     10.75       1.60      21.36  60.4642
   17.3      5.13       1.41      19.61  53.9728

   *** RR:  50
    ** PP: 10
     * ST: 10

   14.8     27.96       1.15       3.32  19.3284
   16.2     17.81       2.57       3.41  20.0315
   17.6     22.72       8.87       2.62  34.8645

     * ST: 20

   15.4     20.67       2.42       2.75  18.8569
   16.4     18.72       5.10       2.91  25.2199
   17.8     34.19      24.66       1.76  74.6022

     * ST: 30

   14.7     27.95       8.64       2.23  34.8688
```

Table O-3 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
15.9	21.00	7.94	2.64	32.1423
18.3	41.87	45.18	1.70	126.7598
~~19.4~~	~~51.01~~	~~82.50~~	~~3.29~~	~~224.8968~~
** PP: 25				
~~* ST: 10~~				
14.7	20.68	.78	1.95	12.8598
~~15.9~~	~~8.04~~	~~.34~~	~~3.26~~	~~11.5793~~
* ST: 20				
14.6	11.40	1.19	1.25	9.3804
16.6	9.46	.68	2.57	11.3537
~~18.5~~	~~14.87~~	~~3.63~~	~~1.15~~	~~10.1022~~
* ST: 30				
14.8	12.47	3.00	1.33	14.3097
18.8	15.04	4.96	2.06	21.6711
~~19.2~~	~~22.10~~	~~21.68~~	~~1.01~~	~~61.9266~~
** PP: 50				
~~* ST: 10~~				
15.4	14.22	1.13	2.51	13.2135
~~15.5~~	~~12.22~~	~~.85~~	~~4.08~~	~~15.0673~~
* ST: 20				
15.3	9.23	1.57	2.71	13.3190
16.2	6.94	1.17	5.39	18.3698
* ST: 30				
~~15.2~~	~~7.65~~	~~2.05~~	~~2.65~~	~~13.8750~~
16.3	6.41	1.78	4.46	17.3768
17.7	8.40	2.29	3.10	15.8060
** PP: 90				
* ST: 20				
15.3	15.26	1.32	8.49	28.9327
16.4	5.21	.95	12.65	35.4744
* ST: 30				
~~15.1~~	~~21.92~~	~~1.88~~	~~10.62~~	~~37.5824~~
16.5	4.86	1.57	14.55	41.6337
16.9	4.71	1.32	11.15	32.4798
*** RP: 100				
** PP: 10				

Table O-3 (Cont.)

PAGE 4 12/6

MEAS AFR	CO	HC	NOX	RANK NO
* ST: 10				
~~15.2~~	~~29.45~~	~~6.03~~	~~2.47~~	~~29.5441~~
16.2	26.93	8.88	2.46	35.7291
17.1	24.95	20.21	2.47	62.8059
~~19.6~~	~~44.42~~	~~36.62~~	~~1.43~~	~~105.9568~~
* ST: 20				
15.1	31.77	10.40	1.79	39.1850
16.1	33.89	20.55	2.18	65.5396
~~18.1~~	~~48.19~~	~~52.76~~	~~1.56~~	~~146.7565~~
19.0	56.62	68.27	1.17	186.0901
~~* ST: 30~~				
13.4	257.22	92.39	1.88	305.6944
~~15.9~~	~~31.83~~	~~21.00~~	~~1.74~~	~~64.9313~~
16.8	53.43	75.14	4.02	209.0330
18.5	49.86	82.22	3.67	224.3763
** PP: 25				
* ST: 10				
14.9	24.93	5.35	1.13	23.2061
17.0	10.72	2.05	1.55	12.0279
~~17.1~~	~~12.36~~	~~1.49~~	~~2.15~~	~~12.6444~~
18.0	11.88	2.79	1.80	14.7990
~~* ST: 20~~				
14.4	29.93	10.64	.88	36.9542
~~16.3~~	~~12.71~~	~~2.24~~	~~1.33~~	~~12.5266~~
18.2	22.67	11.68	.93	37.4805
19.6	34.73	39.30	.93	108.3934
* ST: 30				
~~12.8~~	~~158.57~~	~~26.67~~	~~.72~~	~~113.4870~~
16.5	23.32	22.33	.96	63.7222
16.7	31.83	69.12	.96	180.3471
** PP: 50				
* ST: 10				
15.7	9.93	2.12	1.06	10.7413
16.2	11.26	1.37	2.03	11.7282
~~16.5~~	~~8.04~~	~~.72~~	~~2.20~~	~~9.6208~~
17.4	6.07	.40	3.57	11.6859
~~* ST: 20~~				
15.3	15.62	6.65	.87	22.9886

Table O-3 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
16.4	7.82	1.33	2.50	11.7939
18.0	9.37	1.58	2.28	12.3095
~~19.2~~	~~12.01~~	~~4.59~~	~~1.63~~	~~18.8025~~
* ST: 30				
14.5	28.45	17.52	.63	52.6744
16.0	8.96	3.69	1.72	15.9353
~~17.4~~	~~11.12~~	~~6.74~~	~~1.48~~	~~23.4098~~
20.0	12.11	6.17	1.56	22.5105
~~** PP: 90~~				
* ST: 10				
~~15.4~~	~~15.00~~	~~.72~~	~~5.13~~	~~18.9929~~
16.1	8.17	.40	6.36	19.2786
~~* ST: 20~~				
15.6	9.75	1.09	4.82	17.5762
~~16.8~~	~~5.69~~	~~.88~~	~~7.85~~	~~23.4449~~
17.4	5.00	.81	6.72	20.2462
~~* ST: 30~~				
15.6	7.94	1.70	6.06	21.6316
~~16.4~~	~~4.85~~	~~1.45~~	~~8.02~~	~~25.0131~~
17.1	4.80	1.20	6.37	20.2636
~~**** EI: 1~~				
*** RR: 0				
** PP: 10				
~~* ST: 10~~				
14.8	4.69	.56	4.44	13.8453
~~16.2~~	~~4.88~~	~~.58~~	~~5.62~~	~~11.8900~~
17.4	6.43	1.73	3.02	13.6607
20.0	7.49	5.72	1.93	20.9792
* ST: 20				
~~15.0~~	~~4.10~~	~~1.35~~	~~3.27~~	~~12.6736~~
16.5	4.20	.69	3.22	10.9682
18.4	5.96	4.30	2.52	18.5407
~~19.4~~	~~7.02~~	~~8.69~~	~~1.60~~	~~27.2598~~
* ST: 30				
14.4	3.49	.97	2.87	10.5673
16.2	4.43	4.65	4.52	23.9444
~~18.5~~	~~5.34~~	~~5.13~~	~~4.89~~	~~26.3078~~
19.9	6.66	11.49	4.14	40.3332

Table O-3 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
** PP: 25				
* ST: 10				
13.7	2.50	.30	2.78	8.4170
15.6	2.42	.12	3.13	8.8294
~~16.9~~	~~3.05~~	~~.35~~	~~2.65~~	~~8.3757~~
17.9	3.57	1.13	2.04	8.9061
~~* ST: 20~~				
13.7	2.17	.41	2.87	8.6132
~~16.2~~	~~2.50~~	~~.26~~	~~3.76~~	~~10.7694~~
18.6	3.04	.67	1.73	6.8533
21.1	4.12	6.60	1.10	20.0593
* ST: 30				
~~13.7~~	~~1.81~~	~~.38~~	~~3.41~~	~~10.4720~~
17.4	2.41	.36	2.94	8.9369
20.8	3.14	.97	2.23	8.8644
~~20.9~~	~~3.48~~	~~5.44~~	~~1.27~~	~~17.4668~~
** PP: 50				
~~* ST: 10~~				
14.7	1.57	.44	4.45	12.6599
~~15.5~~	~~2.11~~	~~.30~~	~~6.05~~	~~16.4773~~
16.5	1.73	.13	4.30	11.5759
17.3	1.73	.17	4.18	11.3735
* ST: 20				
~~14.8~~	~~1.55~~	~~.69~~	~~6.42~~	~~18.1848~~
16.5	1.69	.24	8.29	21.8074
18.1	1.87	.20	4.43	12.1128
~~19.4~~	~~2.29~~	~~.73~~	~~2.34~~	~~8.3049~~
* ST: 30				
14.8	1.41	.70	9.12	24.9220
16.1	1.47	.33	9.78	25.6872
~~17.4~~	~~1.54~~	~~.26~~	~~6.81~~	~~18.1121~~
20.1	2.10	.84	2.15	8.0414
~~** PP: 90~~				
* ST: 10				
~~15.0~~	~~1.48~~	~~.29~~	~~9.06~~	~~23.7867~~
16.1	1.44	.14	9.78	25.2150
~~* ST: 20~~				
14.9	1.28	.33	11.64	30.7813

Table O-3 (Cont.)

'PAGE 7 12/6

MEAS AFR	CO	HC	NOX	RANK NO
16.1	1.10	.25	14.08	36.1333
17.4	1.31	.20	11.42	29.4231
* ST: 30				
15.0	1.31	.41	15.30	30.6353
16.3	1.22	.29	20.31	51.8411
17.5	1.21	.31	18.13	46.4370
*** RR: 50				
** PP: 10				
* ST: 10				
14.9	5.13	.46	3.06	10.2808
16.9	5.13	.76	2.95	10.7375
17.6	7.17	2.86	2.62	15.6344
* ST: 20				
15.4	4.33	.90	2.29	9.1937
16.9	4.57	1.46	2.42	10.9551
17.8	6.24	6.87	2.34	24.4414
* ST: 30				
14.7	4.27	2.88	2.02	13.3303
16.9	4.41	3.37	2.20	15.0166
18.3	6.03	9.72	2.55	31.8558
19.4	6.87	13.78	4.58	47.0803
** PP: 25				
* ST: 10				
14.8	2.93	.33	2.28	7.3666
15.9	3.00	.11	3.60	10.1506
* ST: 20				
14.6	2.61	.36	1.25	4.7707
16.6	2.68	.24	2.57	7.7986
18.5	3.06	.95	1.44	6.8171
* ST: 30				
14.8	.20	.97	1.33	5.7497
18.9	2.95	.87	2.63	9.5646
19.2	3.24	5.47	1.58	18.2444
20.7	3.89	12.48	1.04	34.1851
** PP: 50				
* ST: 10				
15.5	1.89	.30	2.43	7.3626

Table O-3 (Cont.)

'PAGE 8 12/6

MEAS AFR	CO	HC	NOX	RANK NO
15.5	2.23	.22	3.97	11.1175
* ST: 20				
15.2	1.57	.47	2.51	7.8831
16.2	1.76	.27	4.95	13.3805
* ST: 30				
15.2	1.49	.59	2.31	7.6523
16.3	1.56	.33	4.24	11.8637
17.7	1.64	.42	3.10	9.2567
** PP: 90				
* ST: 20				
15.3	1.14	.29	8.29	21.7676
16.5	1.19	.19	12.21	31.3384
* ST: 30				
15.1	1.14	.42	10.46	27.5097
16.5	1.26	.32	13.96	36.0511
17.0	1.14	.31	10.24	26.6914
*** RR: 100				
** PP: 10				
* ST: 10				
15.3	6.19	1.21	2.47	10.9468
16.2	5.98	1.78	2.62	12.6503
17.1	7.75	4.47	2.83	20.2569
19.6	8.06	7.11	1.61	23.7371
* ST: 20				
15.0	5.14	2.31	2.05	12.2709
16.2	4.98	3.29	2.59	15.9641
18.1	6.67	14.19	2.19	32.2904
19.0	7.31	12.05	1.67	35.7152
* ST: 30				
13.5	17.22	16.23	1.62	48.7001
15.8	4.94	6.66	1.97	22.6218
16.8	6.29	13.49	4.60	46.2524
18.5	6.61	11.14	4.40	40.1148
** PP: 25				
* ST: 10				
14.9	4.14	1.15	1.22	7.0725
17.0	3.39	.42	1.93	6.8464

Table O-3 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
17.2	3.63	.30	2.49	8.0244
18.0	4.00	.99	1.87	8.2661
* ST: 20				
~~14.3~~	~~3.30~~	~~1.77~~	~~.95~~	~~7.6627~~
16.3	2.91	.48	1.60	6.0266
18.2	3.49	2.34	1.09	9.4588
~~19.6~~	~~4.54~~	~~9.77~~	~~1.12~~	~~27.9646~~
* ST: 30				
13.8	3.09	7.19	.82	20.4954
16.4	2.99	.82	1.29	6.1044
~~16.7~~	~~6.14~~	~~16.86~~	~~1.12~~	~~45.7278~~
19.4	3.74	12.99	1.09	35.2829
** PPI-50				
* ST: 10				
~~15.8~~	~~2.27~~	~~.55~~	~~1.16~~	~~4.9091~~
16.2	2.54	.31	2.03	6.5782
16.5	1.81	.16	2.34	6.7726
~~17.4~~	~~1.89~~	~~.13~~	~~3.29~~	~~9.0989~~
* ST: 20				
15.2	2.07	1.44	.87	6.2960
16.4	1.84	.25	2.76	7.9009
~~18.0~~	~~1.97~~	~~.35~~	~~2.45~~	~~7.5581~~
19.2	2.29	.73	1.93	7.2790
* ST: 30				
14.6	2.14	3.42	.63	10.5459
~~16.0~~	~~1.74~~	~~.54~~	~~1.72~~	~~6.1288~~
17.4	1.91	1.35	1.52	7.6544
20.1	2.09	1.03	2.01	8.1519
** PP: 90				
* ST: 10				
15.4	1.46	.16	5.33	14.1447
16.1	1.56	.10	6.16	16.1027
* ST: 20				
~~15.7~~	~~1.14~~	~~.29~~	~~4.49~~	~~12.2676~~
16.8	1.22	.19	7.59	19.7972
17.3	1.32	.20	6.24	16.4760
* ST: 30				

Table O-4

ENGINE TEST DATA, SHOWING RELATIONSHIP BETWEEN EMISSIONS AND AIR-FUEL RATIO– 1,600 RPM, ENGINE B

```
 PAGE 10 12/6

   MEAS
   AFR        CO        HC       NOX  RANK NO

   15.6      1.22       .38      6.12  16.5857
   16.3      1.20       .29      7.58  20.0103
   17.1      1.27       .30      6.05  16.2302

 ••••• E: B
  •••• C: 0
   ••• RR:  0
    •• PP: 10
     • ST: 10

   14.7     86.44      2.52      3.03  39.1449
   16.2     15.61      3.09      2.99  19.6028
   17.6     17.81      4.27      2.16  21.0529
   19.3     43.27     28.54      1.78  86.7862

     • ST: 20

   14.4     57.19      3.04      2.63  30.8102
   16.7     17.36      2.99      2.48  18.5986
   19.1     40.55     29.61       .63  85.7210
   21.5     61.38    134.98       .96 355.6048

     • ST: 30

   14.0     68.93      4.32      3.10  38.5601
   16.6     18.87      4.06      2.99  22.9274
   18.9     34.58     28.51      1.10  82.6572
   23.1     69.44    121.89       .74 319.5662

    •• PP: 25
     • ST: 10

   14.8     21.44      1.04      2.76  15.7425
   16.4      7.36       .36      3.09  10.7678
   17.7      8.50       .38      2.10   8.6768
   20.9     16.92      3.15      1.35  15.7697

     • ST: 20

   14.9     25.89      1.86      3.95  22.0263
   17.1      8.55       .94      3.25  12.9324
   18.5     11.75      1.94      1.47  11.8626
   22.5     30.06     17.11       .49  51.7979

     • ST: 30

   14.6     28.18      2.38      4.38  25.0431
   17.0      9.34      1.46      3.75  15.6830
   18.8     14.03      3.97      1.38  17.2594
   20.6     24.34     21.98       .71  62.5436

    •• PP: 50
     • ST: 10
```

Table O-4 (Cont.)

```
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   MEAS
   AFR        CO        HC       NOX  RANK NO

   14.8     21.21      1.18      4.75  20.9913
   16.3      5.00       .29      4.91  14.4529
   17.3      5.57       .32      3.35  10.7937

     • ST: 20

   14.5     26.29      1.94      5.98  27.4141
   16.5      5.96       .65      6.35  19.2133
   17.8      6.96       .73      3.87  13.5025
   19.1      9.33      1.44      1.37   9.6813

     • ST: 30

   14.8     18.13      2.20      9.23  33.7732
   16.9      6.47      1.24      9.09  27.5347
   19.2      7.56      1.23      3.54  14.0735
   20.3     11.12      4.06      1.45  16.7980

    •• PP: 90
     • ST: 10

   15.1     21.64      1.46      7.33  28.2507
   16.5      4.88       .55      9.05  25.4018
   16.8      4.49       .47      6.96  19.8669

     • ST: 20

   14.9     19.97      1.65      9.63  33.9729
   15.9      4.85       .95     13.71  38.0185
   16.6      4.95       .69      9.73  27.4638
   18.3      5.88       .71      5.11  16.2361

     • ST: 30

   14.6     30.51      2.14     10.97  41.6180
   16.8      4.73      1.69     16.17  45.7186
   18.7      5.41      1.11      9.60  28.2985
   19.6      6.68      1.34      4.34  16.0830

   ••• RP:  50
    •• PP: 10
     • ST: 10

   14.8     26.33      1.32      5.02  23.5136
   16.0     16.23      2.03      2.25  15.3497
   17.1     21.48      5.31      2.09  24.4939

     • ST: 20

   14.7     23.69      2.15      1.84  16.8115
   16.9     21.67      5.96      1.85  25.5351
   19.2     64.39     72.84      1.08 199.2968
```

Table O-4 (Cont.)

PAGE 12 12/6

MEAS AFR	CO	HC	NOX	RANK NO
♦ ST: 30				
14.7	29.59	7.84	1.74	32.1749
16.1	29.84	19.87	1.65	61.3649
18.6	45.77	55.74	1.00	151.9130
♦♦ PP: 25				
♦ ST: 10				
14.9	12.07	.55	1.81	9.4165
16.1	8.04	.49	1.99	8.5348
17.6	9.54	.62	1.66	8.4681
♦ ST: 20				
14.9	12.06	1.09	1.93	11.0306
16.7	11.27	1.33	1.68	10.7586
18.4	17.07	5.42	.97	20.6651
19.5	23.69	11.87	.66	37.5689
♦ ST: 30				
15.1	11.29	1.68	1.72	11.7181
16.2	14.12	3.81	1.49	17.1706
18.6	20.19	10.76	1.07	34.8571
20.4	28.12	35.03	.58	95.1596
♦♦ PP: 50				
♦ ST: 10				
15.1	8.00	.52	2.34	9.4712
16.2	5.55	.34	3.13	10.2866
♦ ST: 20				
15.2	8.54	1.04	1.89	9.7734
16.6	6.35	.65	2.85	10.5780
17.8	7.02	.66	2.36	9.5745
19.1	14.74	7.10	1.12	24.4524
♦ ST: 30				
15.0	9.17	1.87	3.18	15.2080
16.1	6.65	1.50	3.13	13.4394
18.6	9.69	2.66	1.38	12.7878
19.9	13.32	9.28	.72	28.3518
♦♦ PP: 90				
♦ ST: 20				
15.0	20.74	1.91	5.33	24.0839
16.1	4.78	.80	6.42	19.4071
17.2	4.96	.67	7.06	20.7430

Table O-4 (Cont.)

PAGE 13 12/6

MEAS AFR	CO	HC	NOX	RANK NO
♦ ST: 30				
14.8	18.09	1.95	5.94	24.9267
16.3	5.01	1.42	7.22	22.9869
18.6	5.66	1.08	6.85	21.4239
♦♦♦ RR: 100 -				
♦♦ PP: 10 -				
♦ ST: 10				
16.1	36.03	11.59	1.60	42.8654
16.2	29.71	10.95	1.73	39.7706
17.7	44.55	20.66	1.72	67.7932
19.7	61.49	39.68	1.76	119.2658
♦ ST: 20				
14.8	43.08	13.90	1.25	49.6980
16.9	41.18	23.15	1.38	72.0252
19.2	88.88	130.45	.60	345.8119
21.7	84.41	152.10	.99	398.2771
♦ ST: 30				
13.9	139.90	50.75	1.53	168.7525
15.3	59.56	66.89	1.59	184.6390
19.2	56.90	97.93	.77	257.2498
20.7	70.46	173.19	1.27	446.3132
♦♦ PP: 25				
♦ ST: 10				
15.2	10.76	1.11	1.29	9.0970
16.3	12.28	1.79	1.19	10.9526
17.8	13.87	2.14	1.07	11.9739
19.4	16.05	3.62	1.24	16.6499
♦ ST: 20				
15.0	20.31	6.41	.85	23.7327
16.3	28.14	14.86	1.07	47.1954
18.0	29.27	19.17	.75	57.2399
20.3	41.46	6.96	.30	29.9197
♦ ST: 30				
14.9	28.09	12.42	.90	40.8044
16.0	29.06	27.36	1.01	77.8038
18.2	29.20	30.21	.71	84.0462
19.8	31.81	48.30	.60	128.6608
♦♦ PP: 50				
♦ ST: 10				

Table O-4 (Cont.)

PAGE 14 12/6

MEAS AFR	CO	HC	NOX	RANK NO
15.3	9.55	.81	1.25	7.9094
16.7	6.36	.52	2.13	8.4639
~~17.1~~	~~6.71~~	~~.59~~	~~2.27~~	~~9.0876~~
18.5	9.88	1.63	1.68	11.0815
• ST: 20				
15.2	22.75	5.54	.91	22.4784
~~16.6~~	~~9.22~~	~~1.39~~	~~1.44~~	~~9.7020~~
18.3	11.13	2.02	1.42	11.7504
19.1	14.74	7.10	1.12	24.4524
• ST: 30				
~~15.1~~	~~12.44~~	~~5.08~~	~~.85~~	~~18.1741~~
16.6	13.64	8.10	.94	26.1179
17.8	13.75	10.05	1.19	31.5313
~~19.9~~	~~13.32~~	~~9.28~~	~~.72~~	~~28.3518~~
•• PP: 90 • ST: 10				
15.2	10.41	.67	4.29	15.4209
~~16.2~~	~~4.73~~	~~.51~~	~~7.91~~	~~22.4101~~
16.7	4.45	.47	6.32	18.2552
• ST: 20				
15.2	8.42	2.08	2.91	14.8246
~~16.0~~	~~5.30~~	~~.86~~	~~2.68~~	~~10.3564~~
17.1	5.55	.71	4.28	14.0641
18.1	5.93	.68	4.38	14.3527
• ST: 30				
~~15.3~~	~~10.67~~	~~1.78~~	~~2.04~~	~~12.5797~~
16.2	6.01	1.81	2.38	12.1323
18.4	6.42	1.29	3.66	14.1846
~~19.6~~	~~6.87~~	~~1.50~~	~~3.54~~	~~14.7730~~
•••• C: 1 ••• RR: 0 •• PP: 10 • ST: 10				
14.7	5.24	.63	2.91	10.3528
16.2	6.07	1.80	2.85	13.3005
~~17.6~~	~~6.56~~	~~2.23~~	~~2.46~~	~~13.5184~~
19.3	8.89	10.70	2.37	34.6373
• ST: 20				
14.4	4.80	1.31	2.22	10.1569

Table O-4 (Cont.)

PAGE 15 12/6

MEAS AFR	CO	HC	NOX	RANK NO
16.7	5.13	.90	2.98	11.1539
19.1	6.76	4.11	1.90	16.7626
~~21.5~~	~~9.35~~	~~35.56~~	~~1.77~~	~~93.9067~~
• ST: 30				
14.0	4.09	1.01	2.48	9.8664
16.6	4.42	1.16	2.78	11.0793
~~18.9~~	~~6.98~~	~~4.75~~	~~2.10~~	~~10.6236~~
23.1	8.30	19.96	1.84	55.7241
•• PP: 25 • ST: 10				
~~14.8~~	~~2.59~~	~~.28~~	~~2.65~~	~~8.0697~~
16.4	3.12	.14	2.89	8.4841
17.7	3.47	.16	2.10	6.6608
~~19.7~~	~~4.36~~	~~.82~~	~~1.78~~	~~7.7324~~
• ST: 20				
14.9	2.40	.50	3.34	10.2754
17.1	2.76	.35	3.25	9.7904
~~18.5~~	~~3.24~~	~~.76~~	~~1.02~~	~~7.3566~~
22.5	4.65	3.19	1.27	12.3231
• ST: 30				
14.6	2.12	.60	3.67	11.2619
~~17.0~~	~~2.48~~	~~.53~~	~~3.36~~	~~10.4221~~
18.8	2.97	1.23	1.85	8.4985
20.6	3.58	4.89	1.59	16.9548
•• PP: 50 • ST: 10				
14.8	1.85	.26	4.51	12.4533
16.3	1.96	.08	4.74	12.6216
~~17.3~~	~~2.18~~	~~.11~~	~~3.35~~	~~9.2845~~
18.6	2.48	.31	2.49	7.7105
• ST: 20				
14.5	1.59	.40	5.58	15.3933
~~16.5~~	~~1.77~~	~~.17~~	~~6.12~~	~~16.2358~~
19.1	2.02	.41	1.56	5.4941
24.8	1.82	.24	3.74	10.4707
• ST: 30				
~~14.7~~	~~1.40~~	~~.42~~	~~8.20~~	~~21.9362~~
16.9	1.65	.27	8.36	22.0438
19.2	1.88	.25	3.75	10.5377

Table O-4 (Cont.)

PAGE 16 12/6

MEAS AFR	CO	HC	NOX	RANK NO
20.1	2.00	.61	1.89	6.8010
~~♦♦ PP: 90~~				
♦ ST: 10				
~~15.0~~	~~1.58~~	~~.43~~	~~6.91~~	~~18.7885~~
16.5	1.56	.13	8.62	22.3259
16.8	1.58	.12	7.10	18.5074
♦ ST: 20				
~~14.9~~	~~1.28~~	~~.36~~	~~9.47~~	~~24.9295~~
15.9	1.28	.27	12.40	32.0350
16.6	1.31	.16	9.85	25.4005
~~18.3~~	~~1.58~~	~~.17~~	~~5.32~~	~~14.1793~~
♦ ST: 30				
14.6	1.41	.49	10.76	28.5098
16.8	1.32	.46	15.42	40.0602
~~18.7~~	~~1.49~~	~~.27~~	~~8.89~~	~~23.3218~~
19.6	1.62	.28	4.66	12.8094
~~♦♦♦ RR: 50~~				
♦♦ PP: 10				
♦ ST: 10				
14.8	5.80	.42	2.06	7.8803
16.0	5.81	1.10	2.67	11.0668
~~17.1~~	~~6.83~~	~~1.93~~	~~2.25~~	~~12.3411~~
♦ ST: 20				
14.8	5.47	1.11	1.84	8.9161
16.9	5.62	1.27	2.11	10.0255
~~19.2~~	~~8.14~~	~~15.01~~	~~1.63~~	~~43.0789~~
♦ ST: 30				
14.7	4.76	2.61	1.74	12.1159
16.1	5.02	3.41	1.89	14.5185
~~18.9~~	~~6.42~~	~~9.78~~	~~1.71~~	~~30.0169~~
♦♦ PP: 25				
~~♦ ST: 10~~				
14.9	3.00	.21	1.62	5.4445
~~16.1~~	~~3.29~~	~~.17~~	~~1.99~~	~~6.3573~~
17.5	3.66	.17	1.98	6.4411
~~♦ ST: 20~~				
14.9	2.48	.33	1.65	5.6593

Table O-4 (Cont.)

PAGE 17 12/6

MEAS AFR	CO	HC	NOX	RANK NO
16.7	3.10	.46	1.81	6.5587
18.4	3.56	1.17	1.38	7.3507
~~19.5~~	~~3.90~~	~~2.77~~	~~1.15~~	~~10.7782~~
♦ ST: 30				
15.1	2.41	.50	1.61	5.9533
16.2	2.87	1.05	1.61	7.4301
~~18.6~~	~~3.31~~	~~2.24~~	~~1.50~~	~~10.1869~~
20.4	3.85	9.27	1.16	26.6421
~~♦♦ PP: 50~~				
♦ ST: 10				
~~15.1~~	~~1.94~~	~~.15~~	~~2.09~~	~~6.1614~~
16.2	2.13	.09	3.13	8.6710
~~♦ ST: 20~~				
15.2	1.78	.24	1.89	5.8339
~~16.6~~	~~1.86~~	~~.15~~	~~2.05~~	~~8.0379~~
17.8	1.91	.17	2.27	6.6514
~~♦ ST: 30~~				
14.9	1.49	.40	2.79	8.3688
~~16.1~~	~~1.70~~	~~.27~~	~~3.13~~	~~8.9835~~
18.6	1.95	.55	1.78	6.3650
~~♦♦ PP: 90~~				
♦ ST: 20				
~~15.0~~	~~1.39~~	~~.55~~	~~4.98~~	~~14.2003~~
16.1	1.30	.23	6.21	16.4683
17.2	1.32	.14	6.84	17.8297
♦ ST: 30				
~~14.8~~	~~1.35~~	~~.44~~	~~5.68~~	~~15.5202~~
16.3	1.38	.33	7.01	18.7358
18.6	1.51	.24	6.39	17.0045
♦♦♦ RR: 100				
♦♦ PP: 10				
~~♦ ST: 10~~				
16.1	8.03	1.83	2.14	12.1752
~~16.2~~	~~7.38~~	~~2.08~~	~~2.42~~	~~13.2930~~
17.7	8.35	5.05	2.29	20.4980
19.7	9.89	9.26	2.20	30.9942
♦ ST: 20				

Table O-4 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
14.8	6.60	2.85	1.67	13.0674
16.9	6.55	3.98	1.84	16.2338
~~19.2~~	~~9.24~~	~~28.29~~	~~1.41~~	~~75.2574~~
21.7	9.42	41.83	1.59	108.7700
• ST: 30				
13.9	6.06	8.54	1.53	26.4366
~~15.3~~	~~5.96~~	~~13.55~~	~~1.72~~	~~39.1017~~
18.7	7.36	19.60	1.40	53.4696
20.7	8.60	43.65	1.63	113.0678
•• PP: 25				
• ST: 10				
15.2	3.72	.34	1.37	5.3484
16.2	3.92	.33	1.36	5.3578
~~17.7~~	~~4.12~~	~~.38~~	~~1.42~~	~~5.6886~~
19.4	4.30	.86	1.53	7.1873
• ST: 20				
15.0	3.37	.94	1.14	6.1339
~~16.3~~	~~3.91~~	~~2.38~~	~~1.32~~	~~10.2549~~
18.0	3.98	3.53	1.17	12.7053
20.3	4.93	9.63	.89	27.1628
• ST: 30				
~~14.9~~	~~2.90~~	~~2.21~~	~~1.03~~	~~8.0182~~
16.0	3.43	4.69	1.23	15.5228
18.2	3.72	6.52	1.25	20.1216
~~19.8~~	~~4.10~~	~~12.47~~	~~1.21~~	~~34.6455~~
•• PP: 50				
• ST: 10				
15.3	2.37	.21	1.50	4.9593
~~16.7~~	~~2.35~~	~~.12~~	~~2.33~~	~~6.8089~~
17.1	2.38	.14	2.37	6.9665
18.5	2.64	.47	1.80	6.4228
• ST: 20				
~~15.2~~	~~2.45~~	~~1.27~~	~~1.61~~	~~6.3431~~
16.6	2.22	.28	1.68	5.5359
18.3	2.23	.52	1.78	6.3742
~~19.0~~	~~2.33~~	~~1.25~~	~~1.70~~	~~7.9841~~
• ST: 30				
15.1	1.92	.82	1.11	5.3397
16.6	2.07	1.62	1.17	7.4850

Table O-4 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
17.8	2.21	1.67	1.43	8.2982
19.7	2.25	1.70	1.34	8.1581
•• PP: 90				
• ST: 10				
15.1	1.52	.92	4.29	13.4160
16.2	1.51	.12	7.58	19.6868
~~16.7~~	~~1.64~~	~~.12~~	~~6.32~~	~~16.5759~~
• ST: 20				
15.0	1.39	.64	2.94	9.3198
16.0	1.42	.25	2.84	8.1274
~~17.1~~	~~1.47~~	~~.17~~	~~4.39~~	~~11.8220~~
18.1	1.59	.16	4.59	12.3329
• ST: 30				
15.2	1.46	.45	2.10	6.7770
~~16.2~~	~~1.45~~	~~.43~~	~~2.66~~	~~8.1253~~
18.4	1.64	.31	3.76	19.6385
19.5	1.66	.33	3.80	19.7931

Table O-5

ENGINE TEST DATA, SHOWING RELATIONSHIP BETWEEN EMISSIONS AND AIR-FUEL RATIO – 2,400 RPM, ENGINE A

```
PAGE 1
DATE: 12/6 12:17
DATA BASE: /3.0 E2400/
REPORT FORM: /3.0 RPT2/

  MEAS
  AFR          CO         HC        NOX  RANK NO

♦♦♦♦♦ E: A
 ♦♦♦♦ C: 0
  ♦♦♦ RR:   0
   ♦♦ PP: 10
    ♦ ST: 10

  14.9      27.89        .30       5.52  22.7346
  16.3       8.98        .44       5.54  17.5643
  19.3      15.66       1.87       2.48  15.3669
  21.3      30.72      13.51       2.24  47.5865

    ♦ ST: 20

  14.7      27.59        .83       6.32  25.9391
  16.8       9.75        .63       5.48  18.1042
  17.4      12.94       1.13       5.83  21.1370
  20.9      36.92      16.12       1.78  54.6259

    ♦ ST: 30

  14.7      23.87       1.07       7.75  29.0053
  16.4      12.02       1.17       7.02  23.9390
  18.4      14.56       1.12       9.35  30.3891
  19.7      28.54      11.63       3.22  44.8100

   ♦♦ PP: 25
    ♦ ST: 10

  14.4      52.07        .73       3.75  26.4702
  16.8       5.05        .04       4.52  12.8829
  17.9       4.94        .16       4.52  13.1432
  19.8       6.82        .52       2.57   9.6992

    ♦ ST: 20

  14.8      19.69        .59       5.59  21.2052
  16.2       5.61        .22       4.97  14.6116
  18.5       6.32        .18       3.38  10.7478
  21.2      17.83       6.08       1.01  22.5984

    ♦ ST: 30

  14.8      20.43       1.02       7.88  28.1966
  16.4       6.33        .37       7.23  20.8392
  18.3       7.46        .39       4.09  13.3703
  20.7      19.21       4.91        .89  19.8506

   ♦♦ PP: 50
    ♦ ST: 10
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Table O-5 (Cont.)

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PAGE 2 12/6

  MEAS
  AFR          CO         HC        NCX  RANK NO

  15.0      30.33        .34       6.49  25.9749
  17.0       3.12        .05       6.16  16.4396
  19.2       3.58        .16       3.92  11.2432

    ♦ ST: 20

  15.2      22.00        .78       6.71  25.1480
  16.8       4.96        .32      12.54  33.5893
  18.8       4.45        .14       3.32   9.9503
  20.6       5.30        .26       2.46   8.3430

    ♦ ST: 30

  15.0      20.33       1.08       4.49  19.8386
  16.4       5.34        .70      16.51  44.5529
  19.8       5.51        .30       6.65  18.9773
  20.7       7.79        .79       2.28   9.9180

   ♦♦ PP: KL
    ♦ ST: 20

  15.1      12.92        .96      10.04  31.2415
  16.8       4.15        .29      11.30  30.1779
  17.5       3.77        .35       8.22  22.5125

    ♦ ST: 30

  15.1       4.92       1.64      12.40  36.4471
  16.6       5.59        .46      16.2[illegible]  43.3161
  18.3       5.10        .36      11.54  31.2280
  18.6       4.77        .38      16.19  42.8048

  ♦♦♦ RR:  50
   ♦♦ PP: 10
    ♦ ST: 10

  15.4       9.00        .18       3.94  12.9361
  17.0       9.92        .44       4.51  15.2658

    ♦ ST: 20

  15.4      15.55        .83       3.07  14.2729
  16.6      13.12       1.49       3.47  16.1680
  17.8      20.99       4.83       4.61  29.4790

    ♦ ST: 30

  15.3      17.77       2.24       2.79  17.6649
  16.9      19.38       4.99       3.10  25.6207
  17.4      28.19      12.99       4.77  51.8991
  19.5      32.64      15.41       2.93  54.5104

   ♦♦ PP: 25
```

Table O-5 (Cont.)

PAGE 3 12/6

MEAS AFR	CO	HC	NOX	RANK NO
♦ ST: 10				
15.2	32.86	.37	2.27	16.2421
17.2	5.56	.02	2.86	8.8341
♦ ST: 20				
15.4	12.62	.31	2.95	11.8429
16.0	5.47	.16	2.89	9.2241
21.7	19.61	5.25	1.06	21.2225
♦ ST: 30				
15.4	14.69	.50	4.14	15.8901
16.7	7.17	.36	2.82	10.0369
18.6	9.05	.59	1.53	7.9258
20.8	27.15	13.80	.69	43.3688
♦♦ PP: 50				
♦ ST: 20				
15.1	17.27	.59	3.78	15.9684
17.1	5.20	.29	4.94	14.5867
18.9	4.37	.10	2.73	8.3542
♦ ST: 30				
15.2	13.87	.77	5.76	20.3575
16.9	5.51	.55	4.33	13.7871
18.3	6.05	.34	3.59	11.5837
20.9	8.91	1.24	1.70	9.8950
♦♦ PP: KL				
♦ ST: 20				
16.6	3.86	.23	7.60	20.6963
♦ ST: 30				
15.1	24.83	1.11	9.64	34.1103
16.6	5.43	.39	7.87	22.2233
♦♦♦ RR: 100				
♦♦ PP: 10				
♦ ST: 10				
17.2	12.81	1.46	3.88	17.0286
18.2	13.35	.86	3.34	14.3740
19.1	23.77	7.48	2.05	30.3851
21.9	48.20	28.30	1.91	87.9759
♦ ST: 20				

Table O-5 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
15.6	33.77	9.41	1.56	36.7836
16.9	39.33	18.59	1.90	61.6591
17.8	38.30	19.94	4.14	70.2489
20.7	50.94	30.32	1.42	92.4836
♦ ST: 30				
14.9	118.57	55.86	1.50	174.8674
15.6	92.18	80.19	4.18	233.1471
16.5	46.91	24.38	1.83	77.8355
19.4	48.88	31.60	1.84	96.0496
♦♦ PP: 25				
♦ ST: 10				
15.7	9.12	.39	2.91	10.9086
17.0	6.18	.18	2.35	8.1317
18.0	5.47	.20	3.77	11.5216
19.5	9.94	1.51	2.17	12.0315
♦ ST: 20				
16.0	8.37	.65	1.75	8.4221
16.0	11.12	.64	1.38	8.2816
18.7	8.81	.83	1.97	9.5406
20.2	18.55	1.90	1.17	13.0150
♦ ST: 30				
15.9	13.97	1.86	1.57	12.5704
16.7	12.99	1.81	.54	9.5852
19.0	27.00	16.80	.63	50.4918
20.8	32.55	24.11	.72	70.1784
♦♦ PP: 50				
♦ ST: 10				
15.9	11.52	.12	3.45	12.3059
17.0	8.81	.15	5.44	16.5570
18.7	3.63	.13	4.22	11.9347
♦ ST: 20				
15.6	6.71	.22	2.38	8.4601
17.1	8.09	.92	2.26	10.2733
19.2	5.55	.31	1.99	7.3635
19.9	5.46	.22	2.53	8.4675
♦ ST: 30				
16.2	9.99	.59	2.16	9.7773
16.5	10.78	2.72	1.88	14.5047
19.6	10.54	1.92	1.87	12.4579

Lockheed

Table O-5 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
20.8	14.41	5.65	1.15	20.8937
** PP: KL				
* ST: 20				
15.2	11.97	.70	5.79	19.7029
16.7	4.54	.29	5.19	15.0176
17.6	3.93	.31	5.87	16.5870
* ST: 30				
14.8	24.40	1.04	5.46	23.3631
16.8	7.86	.86	2.87	11.5843
18.3	4.78	.34	11.85	31.8602
19.0	5.64	.36	10.70	29.2869
**** C: 1				
*** RR: 0				
** PP: 10				
* ST: 10				
14.9	4.11	.18	5.63	15.7228
16.4	6.26	.40	5.54	16.6668
19.2	6.57	.65	2.77	10.4427
21.3	7.96	5.18	2.43	21.0503
* ST: 20				
14.7	3.58	.34	5.86	16.6072
16.8	4.67	.56	4.83	14.8144
17.4	4.19	.63	5.83	17.3439
20.9	6.33	4.12	1.34	15.2605
* ST: 30				
14.7	3.30	.30	6.82	18.7523
16.4	3.93	.72	4.80	14.9120
18.4	4.53	.56	9.35	26.0732
19.7	4.76	3.46	3.22	17.8890
** PP: 25				
* ST: 10				
14.4	2.57	.17	4.01	11.1955
16.8	3.09	.01	4.52	12.2332
17.9	2.75	.13	4.39	12.1009
19.8	3.17	.26	3.00	9.0665
* ST: 20				
14.8	2.27	.11	5.41	14.4609
16.5	2.11	.09	5.03	13.4151
18.5	2.13	.03	3.38	9.1496

Table O-5 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
21.2	3.35	2.11	1.58	10.0816
* ST: 30				
14.8	2.09	.21	7.37	19.5519
16.6	2.01	.06	6.70	17.4875
18.3	2.10	.11	4.09	11.1109
20.4	2.83	.68	1.34	5.8409
** PP: 50				
* ST: 10				
15.0	1.70	.08	5.28	13.8951
17.0	1.51	.04	6.16	15.9417
19.2	2.09	.14	3.92	10.7562
* ST: 20				
15.2	1.29	.15	6.49	16.9703
16.8	1.61	.12	12.43	31.8412
18.8	1.87	.06	3.45	9.3213
20.6	1.78	.11	2.64	7.3918
* ST: 30				
15.0	1.44	.20	10.20	26.4113
16.4	1.45	.23	15.87	40.6624
19.8	1.55	.07	6.18	16.0766
20.7	1.76	.32	2.45	7.4231
** PP: KL				
* ST: 20				
15.1	1.94	.68	10.29	27.9541
16.8	1.43	.22	11.16	28.8572
17.5	1.49	.31	8.07	21.3693
* ST: 30				
15.1	2.33	.48	11.89	31.5810
16.6	1.39	.21	15.59	39.8960
18.3	1.59	.15	12.64	32.4335
18.6	1.48	.17	16.46	41.9999
*** RR: 50				
** PP: 10				
* ST: 10				
15.4	4.95	.16	4.31	12.6211
17.1	6.91	.44	4.80	15.1055
* ST: 20				

Table O-5 (Cont.)

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   MEAS
   AFR        CO       HC      NOX  RANK NO

   15.4      4.11      .33     3.07   9.6887
   16.6      5.88      .67     3.47  12.0386
   17.8      5.03     1.61     4.86  17.5562

     * ST: 30

   15.3      4.19      .73     2.60   9.5128
   16.8      4.71     1.33     3.10  12.3792
   17.4      4.70     3.69     4.77  22.3074
   19.5      5.19     4.84     3.41  21.8563

    ** PP: 25
     * ST: 10

   15.2      3.36      .15     2.58   7.8041
   17.2      3.40      .01     3.13   8.8494

     * ST: 20

   15.4      2.48      .06     2.86   8.0258
   16.0      2.15      .07     3.00   8.3031
   21.7      3.54     1.33     1.41   7.8101

     * ST: 30

   15.4      1.74      .11     3.70  10.0301
   16.1      2.04      .08     2.88   7.9834
   18.8      2.58      .30     1.83   6.0655
   20.8      3.10     2.51     1.24  10.1337

    ** PP: 50
     * ST: 20

   15.1      1.37      .12     3.95  10.5706
   17.1      1.69      .11     4.87  12.9404
   18.9      1.81      .03     2.89   7.8395

     * ST: 30

   15.2      1.49      .17     5.39  14.3279
   16.9      1.48      .19     4.26  11.5487
   18.3      1.50      .09     3.59   9.6357
   20.9      1.79      .32     1.96   6.2070

    ** PP: RL
     * ST: 20

   16.6      1.44      .17     7.60  19.8382

     * ST: 30

   15.1      1.68      .36     9.64  25.4722
   16.6      1.40      .16     7.48  19.5020
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Table O-5 (Cont.)

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   MEAS
   AFR        CO       HC      NOX  RANK NO

   *** RR: 100
    ** PP: 10
     * ST: 10

   17.2      7.29      .58     3.88  13.2588
   18.2      6.39      .34     3.34  11.0587
   19.1      7.30     1.86     2.40  12.6836
   21.9      9.54     8.42     2.33  29.1675

     * ST: 20

   15.6      5.55     1.96     1.82  10.9628
   16.9      7.13     4.29     1.90  17.3105
   17.8      5.88     3.99     4.28  22.1611
   20.7      6.90     7.96     1.89  26.1690

     * ST: 30

   14.9      7.94     9.74     1.25  29.2164
   15.6     19.66    17.31     3.66  54.5048
   16.5      5.89     4.33     1.83  16.8683
   19.4      5.59     7.11     2.63  25.5606

    ** PP: 25
     * ST: 10

   15.7      3.54      .11     2.86   6.4095
   17.0      3.67      .04     2.35   7.0529
   18.0      3.42      .14     4.18  11.7973
   19.5      3.34      .52     2.34   8.1006

     * ST: 20

   16.0      2.79      .14     1.82   5.7121
   16.9      3.05      .19     1.63   5.4355
   18.7      3.34      .39     1.97   6.6391
   20.3      3.36     1.46     1.59   8.5242

     * ST: 30

   15.9      2.83      .38     1.70   6.0092
   16.7      2.51      .20     1.46   4.8760
   19.0      3.35     2.38      .99   9.2652
   20.8      3.61     4.20     1.12  14.1957

    ** PP: 50
     * ST: 10

   15.9      1.76      .05     3.52   9.4396
   17.0      5.73      .08     5.22  14.9304
   18.7      2.12      .12     4.22  11.4662

     * ST: 20
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Table O-6

ENGINE TEST DATA, SHOWING RELATIONSHIP BETWEEN EMISSIONS AND AIR-FUEL RATIO – 2,400 RPM, ENGINE B

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    MEAS
    AFR        CO        HC        NOX   RANK NO

    15.6      1.41       .08      2.46    6.7598
    17.2      1.96       .25      2.34    7.0362
    19.2      2.08       .08      2.23    6.3819
    19.9      1.84       .09      2.73    7.5857

      * ST: 30

    16.2      1.71       .13      2.37    6.7450
    16.6      1.79       .68      1.96    7.0650
    19.6      1.81       .35      2.21    6.9110
    20.8      2.02      1.16      1.54    7.2734

     ** PP: KL
      * ST: 20

    15.2      1.80       .51      5.79   16.2483
    16.7      1.60       .27      5.19   14.1041
    17.5      1.54       .26      5.68   15.2871

      * ST: 30

    14.8      2.17       .39      5.54   15.4395
    16.6      1.60       .27      3.03    8.7041
    18.3      1.49       .14     11.58   29.7297
    19.0      1.74       .14     10.40   26.8532

 ***** E: B
  **** C: 0
   *** RR:   0
    ** PP: 10
     * ST: 10

    15.0     42.61      1.98      5.36   30.7616
    16.4     10.73       .70      5.99   19.8382
    18.8     14.15      1.23      4.03   17.2368
    20.8     39.61     14.01      2.51   49.4487

      * ST: 20

    14.7     62.92      3.24      6.27.  42.0833
    16.5     11.18      1.08      6.59   22.3974
    18.3     15.23      2.13      3.90   19.4245
    21.8     64.84     48.66      1.47  141.4285

      * ST: 30

    14.3     42.49      2.37      7.73   37.7496
    16.3     12.10       .98      7.23   24.0241
    17.8     16.01      2.25      4.76   22.0964
    21.9     77.39     73.50       .68  203.7301

     ** PP: 25
      * ST: 10
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Table O-6 (Cont.)

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  PAGE 10 12/6

    MEAS
    AFR        CO        HC        NOX   RANK NO

    14.9     36.95      1.25      5.66   28.0664
    19.3      7.49       .42      3.81   12.7523

      * ST: 20

    14.8     22.06      1.49      7.25   28.2474
    16.6      7.61      2.11     11.24   35.4846
    18.5      9.41      2.02      3.45   16.4195
    21.3     29.05     13.63      1.32   45.0880

      * ST: 30

    14.5     17.66      2.15     10.49   36.6630
    16.3      8.83      1.06     10.93   32.5074
    18.1     10.41       .88      5.74   19.5581
    21.9     28.71     16.16       .81   49.8838

     ** PP: 50
      * ST: 10

    15.3     29.69       .93      7.85   30.6756
    17.2      4.80       .31      8.54   23.5179

      * ST: 20

    15.3     29.69      1.61     10.77   39.5842
    17.0      6.03       .51     11.44   31.6174
    19.2      6.43       .44      6.07   18.1393

      * ST: 30

    15.1     35.44      2.16     13.12   48.4918
    16.9      6.64       .97     14.94   41.6688
    18.7      7.13       .71      9.37   27.2538
    20.7     11.50      3.38      4.58   23.0763

     ** PP: KL
      * ST: 20

    15.5     31.25      1.48     12.40   43.8009
    16.9      4.60       .33     11.42   30.7078
    17.0      4.32       .26     10.09   27.1247
    18.6      4.50       .28      7.12   19.8065

      * ST: 30

    15.5     29.90      2.03     12.49   44.9703
    17.4      5.49       .63     16.69   44.8763
    18.2      5.61       .54     14.27   38.6421
    19.4      5.95       .49     10.79   29.9201

   *** RR:  50
    ** PP: 10
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Table O-6 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
* ST: 10				
15.3	4.10	.36	4.57	13.5089
16.5	11.07	.61	4.75	16.6187
* ST: 20				
15.3	17.50	1.98	2.85	17.1013
16.2	13.61	1.81	3.23	16.4926
18.4	22.03	4.92	2.18	23.9294
* ST: 30				
15.4	19.62	1.57	4.01	19.6249
16.1	17.03	3.34	3.70	22.4052
17.6	28.46	11.40	2.19	41.4255
** PP: 25				
* ST: 10				
15.5	20.71	.82	3.75	17.4662
* ST: 20				
15.2	12.00	.95	3.58	14.7965
16.4	8.50	1.17	4.65	16.9787
18.9	9.81	.68	3.08	12.2438
* ST: 30				
15.9	9.16	1.27	3.40	14.2917
16.0	8.25	1.06	8.04	25.1118
18.2	11.72	.85	3.93	15.3452
20.7	38.56	45.37	.60	123.4997
** PP: 50				
* ST: 20				
15.4	20.50	1.20	6.09	24.1812
17.1	5.56	.45	7.38	21.1829
* ST: 30				
15.0	31.33	1.96	7.11	31.7702
16.8	7.18	.93	6.29	25.1051
18.9	8.40	.83	5.88	19.1959
** PP: RL				
* ST: 20				
16.9	4.68	.33	8.01	22.2063
* ST: 30				

Table O-6 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
14.8	3.14	1.89	6.09	20.7583
17.1	5.70	.54	8.35	23.8685
18.2	5.77	.47	9.73	27.1684
*** RR: 100				
** PP: 10				
* ST: 10				
15.9	21.09	1.81	3.16	18.5176
16.5	13.88	1.33	3.65	16.4513
18.7	14.47	1.43	3.80	17.2437
19.7	32.27	17.62	2.97	59.8918
* ST: 20				
16.0	57.33	25.02	1.54	81.7362
16.3	27.23	7.65	1.85	31.2924
18.2	41.60	22.77	1.36	71.1719
20.7	64.35	52.32	1.45	150.1612
* ST: 30				
15.0	66.92	26.35	1.57	87.8756
15.8	60.04	30.91	1.75	97.4241
17.0	60.06	57.13	1.57	160.9312
21.6	83.11	128.34	.69	339.1935
** PP: 25				
* ST: 10				
16.4	13.69	.67	2.65	12.2856
19.5	10.82	1.80	3.55	16.4476
* ST: 20				
15.6	13.76	1.01	2.05	11.6355
16.6	27.53	12.27	1.29	41.2489
18.0	24.70	11.82	1.47	39.7690
21.2	36.05	23.31	1.16	70.3566
* ST: 30				
15.4	28.03	9.62	1.52	35.5075
16.4	9.44	1.12	3.82	15.0582
18.4	15.76	1.93	2.00	14.3426
20.2	38.51	44.55	.60	121.4850
** PP: 50				
* ST: 10				
15.8	14.14	.50	5.55	19.2533
17.7	4.55	.36	6.87	19.3913

Table O-6 (Cont.)

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MEAS
AFR          CO        HC        NOX  RANK NO

   * ST: 20

16.1      12.21       .82       3.34  13.9412
17.5       6.50       .57       4.08  13.5020
19.8       7.23       .59       4.65  15.1905

   * ST: 30

15.7      16.43      1.35       2.54  14.4750
17.1       9.49      1.30       3.68  15.1619
18.8      10.97      1.41       3.57  15.5905
20.8      16.34      6.23       2.49  26.2260

  ** PP: KL
   * ST: 20

15.5      37.30      1.34       7.91  34.0139
16.9       4.60       .33       5.18  15.1078
17.3       4.49       .27       5.67  16.1541
18.5       4.76       .25       6.90  19.2598

   * ST: 30

15.4      19.97      1.49       2.99  16.9827
17.3       6.41       .72       4.24  14.2414
18.2       6.25       .65       5.77  17.8486
19.5       6.42       .62       9.27  26.5754

**** C: 1
 *** RR:   0
  ** PP: 10
   * ST: 10

15.0       4.13       .53       5.58  16.4574
16.4       4.43       .23       6.58  18.3139
18.8      14.15       .26       4.34  15.6459
20.8       8.43     17.43       2.94  52.3416

   * ST: 20

14.7       3.60       .78       5.02  15.5113
16.5       3.77       .29       6.79  18.7911
18.3       4.74       .47       4.37  13.4655
21.8       8.72     18.59       1.65  52.0312

   * ST: 30

14.3       3.35       .50       6.99  19.6798
16.1       3.27       .22       6.81  18.5234
17.8       3.78       .37       5.39  15.4892
21.9       8.06     22.48       1.70  51.4499

  ** PP: 25
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Table O-6 (Cont.)

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MEAS
AFR          CO        HC        NOX  RANK NO

   * ST: 10

14.7       2.57       .22       5.70  15.5425
19.5       3.49       .16       4.09  11.6417

   * ST: 20

14.8       2.18       .30       6.95  18.7479
16.6       1.92       .92      10.42  28.8586
18.7       2.88       .37       3.78  11.1995
21.1       4.22      3.66       1.97  15.0930

   * ST: 30

14.7       1.82       .74       9.74  26.6902
16.2       1.94       .22      10.68  27.8072
18.1       2.64       .15       5.74  15.4923
22.1       3.65      3.32       1.54  13.0211

  ** PP: 50
   * ST: 10

15.3       2.11       .21       8.10  21.3828
17.2       1.86       .10       8.26  21.4410

   * ST: 20

15.3       1.76       .34      10.77  28.2719
17.0       1.52       .14      11.12  28.5805
19.2       1.85       .18       6.21  16.5081

   * ST: 30

15.1       1.64       .42      13.24  34.6067
17.0       1.61       .20      15.07  38.6363
18.5       1.67       .24       9.21  24.1015
20.6       1.98      1.78       4.82  16.9738

  ** PP: KL
   * ST: 20

15.5       2.09       .49      12.50  33.0598
16.9       1.51       .11      11.13  28.5374
17.0       1.48       .09       9.52  24.4548
18.6       1.67       .14       7.12  18.6326

   * ST: 30

15.5       1.85       .63      12.77  34.0957
17.4       1.57       .17      16.69  42.6014
18.2       1.51       .19      14.43  36.9825
19.6       1.65       .19      10.87  28.1237
```

Table O-6 (Cont.)

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   MEAS
   AFR        CO        HC       NOX   RANK NO

   ••• RR:  50
    •• PP: 10
     • ST: 10

   15.3      4.10       .36      4.57  13.5089
   16.5      5.12       .20      5.16  14.8937

     • ST: 20

   15.3      4.01       .63      2.85   9.8410
   16.2      4.06       .45      3.55  11.1667
   18.4      5.80      1.23      2.86  11.8559

     • ST: 30

   15.4      3.92       .54      4.01  12.4950
   16.2      3.65      1.02      3.80  13.0613
   17.6      4.70      2.46      2.92  14.6824

    •• PP: 25
     • ST: 10

   15.5      2.91       .15      3.95  11.0967
   19.4     10.82      1.80      3.55  16.4476

     • ST: 20

   15.2      2.37       .16      3.57  10.0123
   16.4      2.01       .39      4.58  12.9924
   18.9      2.97       .23      3.42   9.9885

     • ST: 30

   15.8      1.94       .42      3.39  10.0700
   16.0      1.86       .20      7.84  20.6349
   18.1      2.76       .16      4.05  11.3270
   20.9      4.09     11.40      1.03  31.5828

    •• PP: 50
     • ST: 20

   15.5      1.82       .24      6.06  16.2707
   17.1      1.67       .12      7.38  19.2339

     • ST: 30

   15.0      1.56       .37      7.20  19.3613
   16.9      1.64       .20      8.29  21.6952
   18.8      1.78       .23      6.21  16.6095

    •• PP: KL
     • ST: 20
```

Table O-6 (Cont.)

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   MEAS
   AFR        CO        HC       NOX   RANK NO

   16.9      1.45       .11      8.01  20.7198

     • ST: 30

   14.8      2.18       .54      6.30  17.7082
   17.1      1.62       .16      8.56  22.2667
   18.2      1.71       .15      9.73  25.1938

   ••• RR: 100
    •• PP: 10
     • ST: 10

   15.9      5.68       .54      3.61  12.0127
   16.5      5.74       .40      3.95  12.5388
   18.7      6.56       .44      4.12  13.3026
   19.7      9.55      7.66      2.97  28.9168

     • ST: 20

   15.9      6.16      4.52      1.84  17.4362
   16.3      5.32      1.67      2.38  11.5879
   18.2      6.44      5.01      2.12  19.4136
   20.7      8.82     20.94      1.81  58.1923

     • ST: 30

   15.0      6.83      4.36      1.80  17.1430
   16.1      7.73      6.88      2.03  24.1290
   17.0      5.94     11.76      1.90  35.1809
   21.6      8.45     45.98      1.39 118.1066

    •• PP: 25
     • ST: 10

   16.5      3.63       .16      2.82   8.5079
   19.6      3.99       .31      3.55  10.8046

     • ST: 20

   15.6      2.71       .22      2.35   7.2086
   16.6      3.21      1.79      1.35   8.6850
   18.0      3.69      1.78      2.13  10.7518
   21.2      4.38      5.44      1.55  18.4315

     • ST: 30

   15.6      2.72      1.69      1.92   9.7220
   16.4      2.07       .22      3.85  10.7704
   18.4      3.01       .30      2.67   8.2920
   20.2      4.02      7.65      1.19  22.8159

    •• PP: 50
     • ST: 10
```

Table O-6 (Cont.)

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MEAS AFR	CO	HC	NOX	RANK NO
15.8	2.07	.13	5.69	15.1509
17.7	2.03	.10	6.87	18.0160
* ST: 20				
16.0	2.08	.21	3.50	9.8740
17.5	1.80	.16	4.17	11.3447
19.6	2.19	.29	4.78	13.0819
* ST: 30				
15.7	1.74	.33	2.81	8.3416
17.0	1.84	.26	4.03	11.2503
18.6	1.94	.45	4.02	11.7329
20.9	2.28	1.96	3.52	14.2511
** PP: KL				
* ST: 20				
15.6	2.41	.42	8.30	22.4832
16.8	1.51	.10	5.34	14.0674
17.3	1.58	.09	5.88	15.3842
18.5	1.71	.11	6.90	18.0212
* ST: 30				
15.4	1.93	.50	3.04	9.5122
17.3	1.79	.20	4.40	12.0143
18.2	1.80	.21	5.97	15.9666
19.5	1.68	.21	9.03	23.5613

Appendix P

ENGINE TEST DATA – COMPUTER SORT BY SPEED, PERCENT POWER, AND TOTAL WEIGHTED EMISSIONS

This appendix contains a series of tables presenting computer-sorted speed, percent power, and total weight emission data. Following are definitions of pertinent abbreviations and column headings:

SCR	Total weighted emission = $(CO/3.4) + (HC/0.41) + (0.40)$
E	Engine
C	Catalyst
RR	Exhaust recirculation rate
PP	Percent power
ST	Spark timing (°BTC)
MAFR	Measuring air-fuel ratio
SFC	Specific fuel consumption
CO	CO emission (g/bhp-hr)
HC	HC emission (g/bhp-hr)
NO	NO_x emission (g/bhp-hr)

Table P-1

COMPUTER-SORTED SPEED, PERCENT POWER, AND TOTAL WEIGHTED EMISSION DATA – 1,200 RPM, ENGINES A AND B (PRINTED FOR SCR < 19)

E	C	RR	PP	ST	MAFR	CAFR	IAR	PO	ER	ET	MP	SFC	CO	HC	NO	SCR
~~A~~	~~1~~	~~050~~	~~10~~	~~10~~	~~14.9~~	~~14.6~~	~~134.2~~	~~4.9~~	~~4.5~~	~~1201~~	~~11.8~~	~~1.82~~	~~4.03~~	~~.49~~	~~1.65~~	~~6.505416~~
A	1	000	10	10	10.7	19.0	111.2	4.9	.0	1191	15.2	2.10	3.32	1.74	.68	6.920373
A	1	000	10	10	17.5	17.4	161.2	4.9	.0	1193	12.8	1.86	4.98	.86	1.49	7.287267
~~A~~	~~1~~	~~050~~	~~10~~	~~20~~	~~15.1~~	~~14.8~~	~~122.0~~	~~4.9~~	~~7.1~~	~~1160~~	~~11.8~~	~~1.64~~	~~4.23~~	~~1.41~~	~~1.13~~	~~7.508142~~
A	1	000	10	10	15.8	16.1	128.2	4.9	.0	1151	11.4	1.64	4.34	.47	2.38	8.372812
A	1	000	10	10	14.1	14.6	121.5	4.9	.0	1158	10.2	1.74	3.77	.96	2.06	8.600287
~~A~~	~~1~~	~~000~~	~~10~~	~~20~~	~~14.4~~	~~14.8~~	~~104.0~~	~~4.9~~	~~.0~~	~~1081~~	~~8.4~~	~~1.45~~	~~3.61~~	~~1.16~~	~~2.01~~	~~8.916033~~
B	1	050	10	10	14.7	14.7	131.2	3.9	5.2	1250	12.1	2.28	5.61	1.50	1.54	9.158537
A	1	100	10	10	14.5	14.6	165.7	4.9	14.5	1231	16.0	2.30	5.14	1.62	1.54	9.312984
~~A~~	~~1~~	~~000~~	~~10~~	~~20~~	~~15.8~~	~~16.2~~	~~121.8~~	~~4.9~~	~~.0~~	~~1100~~	~~10.6~~	~~1.56~~	~~3.89~~	~~.85~~	~~2.45~~	~~9.342288~~
B	1	050	10	20	15.0	14.7	115.7	3.9	4.8	1217	10.4	1.97	4.53	1.63	1.80	9.807963
A	1	000	10	20	17.2	17.6	138.0	4.9	.0	1110	10.9	1.62	4.52	2.11	1.38	9.925753
~~A~~	~~1~~	~~050~~	~~10~~	~~30~~	~~15.1~~	~~14.8~~	~~121.1~~	~~4.9~~	~~9.8~~	~~1133~~	~~11.2~~	~~1.62~~	~~3.75~~	~~2.25~~	~~1.49~~	~~10.315746~~
A	1	050	10	20	16.0	16.0	139.5	4.9	9.5	1162	13.0	1.76	4.46	2.40	1.29	10.390423
B	1	000	10	10	16.4	16.5	138.0	3.9	.0	1219	11.6	2.15	5.74	1.46	2.16	10.649211
~~A~~	~~1~~	~~050~~	~~10~~	~~10~~	~~14.8~~	~~18.8~~	~~116.2~~	~~4.9~~	~~3.1~~	~~1177~~	~~16.2~~	~~2.18~~	~~3.58~~	~~3.22~~	~~.71~~	~~10.6816~~[illegible]
B	1	000	10	10	14.4	14.7	118.1	3.9	.0	1197	10.4	2.10	5.19	1.67	2.19	11.074641
B	1	050	10	10	16.4	16.5	149.3	3.9	4.5	1246	12.9	2.33	6.39	2.19	1.60	11.220875
~~A~~	~~1~~	~~050~~	~~10~~	~~30~~	~~16.3~~	~~16.5~~	~~120.6~~	~~4.9~~	~~5.4~~	~~1082~~	~~11.6~~	~~1.50~~	~~3.63~~	~~2.37~~	~~1.87~~	~~11.523135~~
A	1	000	10	30	16.3	16.6	116.1	4.9	.0	1041	10.4	1.43	3.93	1.47	2.87	11.916248
A	0	000	10	10	15.8	16.1	128.2	4.9	.0	1152	11.4	1.64	13.61	1.22	2.25	12.603551
~~A~~	~~0~~	~~050~~	~~10~~	~~10~~	~~14.9~~	~~14.8~~	~~134.2~~	~~4.9~~	~~4.5~~	~~1205~~	~~11.8~~	~~1.82~~	~~15.99~~	~~1.18~~	~~2.07~~	~~12.7559~~[illegible]
A	1	000	10	30	17.9	18.1	129.3	4.9	.0	1054	11.7	1.45	4.11	2.63	2.08	12.823458
A	1	000	10	30	14.9	14.8	98.2	4.9	.0	0995	9.0	1.33	6.56	2.29	2.28	13.214778
~~B~~	~~1~~	~~000~~	~~10~~	~~20~~	~~16.4~~	~~16.8~~	~~119.8~~	~~3.9~~	~~.0~~	~~1112~~	~~10.5~~	~~1.87~~	~~5.55~~	~~2.53~~	~~2.22~~	~~13.353085~~
A	1	050	10	10	16.2	16.1	165.7	4.9	9.7	1212	14.6	2.06	5.30	3.08	1.79	13.546019
A	1	100	10	10	10.3	18.3	117.5	4.9	6.5	1167	18.4	2.30	3.73	4.56	.72	14.019010
~~B~~	~~1~~	~~000~~	~~10~~	~~10~~	~~18.5~~	~~18.4~~	~~171.9~~	~~3.9~~	~~.0~~	~~1234~~	~~13.8~~	~~2.38~~	~~7.31~~	~~3.52~~	~~1.50~~	~~14.4053~~[illegible]
B	1	000	10	20	14.7	14.6	99.8	3.9	.0	1119	9.3	1.74	4.15	3.05	2.34	14.509613
B	1	000	10	30	14.3	14.5	98.7	3.9	.0	1088	8.8	1.76	4.23	2.96	2.51	14.738630
~~B~~	~~1~~	~~100~~	~~10~~	~~10~~	~~14.9~~	~~14.7~~	~~168.1~~	~~3.9~~	~~14.4~~	~~1307~~	~~16.3~~	~~2.89~~	~~7.40~~	~~3.56~~	~~1.97~~	~~15.784397~~
B	1	050	10	30	14.7	14.5	109.9	3.9	8.9	1150	10.6	1.92	4.44	4.26	1.72	15.996126
A	0	000	10	20	15.8	16.1	121.8	4.9	.0	1099	10.6	1.56	15.46	2.32	2.35	16.080595
~~B~~	~~1~~	~~050~~	~~10~~	~~20~~	~~16.8~~	~~16.7~~	~~124.3~~	~~3.9~~	~~4.7~~	~~1144~~	~~11.6~~	~~1.89~~	~~5.91~~	~~3.94~~	~~1.94~~	~~16.197991~~
B	1	100	10	10	16.4	16.3	178.7	3.9	11.1	1276	16.1	2.79	7.86	4.42	1.57	17.017253
A	0	000	10	10	17.5	17.4	161.2	4.9	.0	1187	12.8	1.86	16.00	3.29	1.74	17.080273
~~B~~	~~1~~	~~100~~	~~10~~	~~20~~	~~14.9~~	~~14.6~~	~~131.5~~	~~3.9~~	~~12.7~~	~~1255~~	~~12.5~~	~~2.25~~	~~5.47~~	~~5.03~~	~~1.54~~	~~17.727116~~
A	1	000	10	20	19.2	19.0	165.4	4.9	.0	1112	13.4	1.74	5.40	5.34	1.27	17.787626
A	1	100	25	30	14.8	14.7	154.3	12.4	15.0	1127	15.1	.84	2.03	.86	.86	4.844620
~~A~~	~~1~~	~~100~~	~~25~~	~~20~~	~~14.8~~	~~14.7~~	~~179.5~~	~~12.4~~	~~13.5~~	~~1187~~	~~16.7~~	~~.98~~	~~2.36~~	~~.83~~	~~.89~~	~~4.943508~~
A	1	100	25	20	16.1	15.9	184.0	12.4	11.1	1165	16.3	.92	2.29	.55	1.25	5.139993
B	1	050	25	10	17.3	17.3	200.4	9.8	3.9	1242	16.5	1.18	3.49	.42	1.24	5.150861
~~B~~	~~1~~	~~100~~	~~25~~	~~10~~	~~16.2~~	~~16.1~~	~~195.8~~	~~9.8~~	~~9.8~~	~~1263~~	~~17.4~~	~~1.23~~	~~3.32~~	~~.48~~	~~1.22~~	~~5.256026~~
B	1	000	25	10	17.5	17.6	186.8	9.8	.0	1219	15.5	1.09	3.25	.31	1.44	5.311980
B	1	050	25	10	14.9	14.6	168.2	9.8	5.9	1248	14.8	1.15	2.94	.45	1.37	5.387267
~~A~~	~~1~~	~~050~~	~~25~~	~~20~~	~~14.6~~	~~14.7~~	~~154.8~~	~~12.4~~	~~5.3~~	~~1152~~	~~13.2~~	~~.86~~	~~1.92~~	~~.43~~	~~1.53~~	~~5.438486~~
A	1	050	25	10	15.7	15.9	196.9	12.4	7.3	1201	17.3	1.01	2.22	.41	1.58	5.602941
B	1	050	25	10	16.0	16.0	173.0	9.8	4.0	1234	15.0	1.10	3.03	.30	1.68	5.822884
~~A~~	~~1~~	~~050~~	~~25~~	~~20~~	~~16.0~~	~~16.0~~	~~157.1~~	~~12.4~~	~~4.7~~	~~1124~~	~~13.6~~	~~.79~~	~~2.07~~	~~.29~~	~~1.85~~	~~5.941141~~
B	1	050	25	20	15.3	14.6	151.2	9.8	7.8	1170	13.3	1.01	2.57	.62	1.47	5.943077
B	1	100	25	10	14.9	14.9	204.6	9.8	12.0	1299	18.7	1.39	3.67	.72	1.27	6.010509
~~A~~	~~1~~	~~050~~	~~25~~	~~30~~	~~14.3~~	~~14.7~~	~~131.6~~	~~12.4~~	~~5.6~~	~~1062~~	~~12.4~~	~~.74~~	~~1.73~~	~~.56~~	~~1.79~~	~~6.349677~~
A	1	050	25	10	16.5	17.1	197.7	12.4	3.7	1182	17.3	.97	2.52	.31	1.95	6.372274
B	1	050	25	20	16.5	16.2	157.0	9.8	4.9	1149	13.4	.97	2.75	.62	1.71	6.596019
~~B~~	~~1~~	~~000~~	~~25~~	~~10~~	~~19.7~~	~~18.9~~	~~232.8~~	~~9.8~~	~~.0~~	~~1227~~	~~18.0~~	~~1.20~~	~~3.93~~	~~.95~~	~~1.26~~	~~6.622956~~
B	1	100	25	20	15.2	14.6	173.8	9.8	16.3	1210	17.0	1.16	3.04	1.38	.95	6.634971
B	1	050	25	20	18.1	17.8	18.2	9.8	4.5	1152	15.3	1.02	3.16	1.22	1.12	6.705022

Table P-1 (Cont.)

~~A~~	~~1~~	~~100~~	~~25~~	~~10~~	~~16.3~~	~~16.7~~	~~221.9~~	~~12.4~~	~~7.7~~	~~1207~~	~~18.3~~	~~1.10~~	~~2.83~~	~~.74~~	~~1.64~~	~~6.737231~~
B	1	100	25	20	16.0	16.0	181.3	9.8	12.8	1188	16.7	1.15	3.17	1.27	1.13	6.854914
A	1	050	25	10	15.0	14.6	178.8	12.4	5.7	1201	14.9	.96	2.28	.90	1.65	6.900710
~~B~~	~~1~~	~~100~~	~~25~~	~~30~~	~~14.9~~	~~14.6~~	~~147.5~~	~~9.8~~	~~12.8~~	~~1160~~	~~14.3~~	~~1.01~~	~~2.30~~	~~1.31~~	~~1.26~~	~~7.021593~~
B	1	100	25	10	17.3	17.2	227.8	9.8	9.0	1267	19.4	1.34	4.08	1.27	1.15	7.172561
B	1	000	25	10	16.2	16.1	161.6	9.8	.0	1206	13.4	1.02	2.91	.36	2.20	7.233931
~~B~~	~~1~~	~~050~~	~~25~~	~~30~~	~~16.3~~	~~16.2~~	~~146.6~~	~~9.8~~	~~7.9~~	~~1115~~	~~13.2~~	~~.91~~	~~2.50~~	~~1.30~~	~~1.37~~	~~7.331026~~
A	1	000	25	30	17.5	18.1	166.6	12.4	.0	1067	13.3	.77	2.18	.55	2.15	7.357640
B	1	050	25	30	14.8	14.7	131.7	9.8	5.0	1094	11.6	.90	2.05	.71	2.04	7.434648
~~B~~	~~1~~	~~000~~	~~25~~	~~20~~	~~16.4~~	~~16.4~~	~~142.8~~	~~9.8~~	~~.0~~	~~1112~~	~~11.9~~	~~.88~~	~~2.43~~	~~.57~~	~~2.22~~	~~7.654950~~
B	1	000	25	20	17.9	18.0	168.7	9.8	.0	1131	14.0	.96	2.86	1.26	1.56	7.814347
A	1	050	25	30	16.2	16.2	158.9	12.4	6.3	1102	13.3	.79	2.21	.56	2.36	7.915854
~~A~~	~~1~~	~~000~~	~~25~~	~~10~~	~~16.7~~	~~17.2~~	~~190.2~~	~~12.4~~	~~.0~~	~~1164~~	~~15.1~~	~~.92~~	~~2.42~~	~~.25~~	~~2.69~~	~~8.046521~~
A	1	050	25	30	17.3	17.9	178.4	12.4	6.2	1076	14.8	.83	2.40	1.58	1.42	8.109541
B	1	000	25	20	14.6	14.6	128.7	9.8	.0	1100	11.1	.89	2.25	.69	2.40	8.344692
~~B~~	~~1~~	~~000~~	~~25~~	~~10~~	~~14.6~~	~~14.5~~	~~150.0~~	~~9.8~~	~~.0~~	~~1190~~	~~12.2~~	~~1.05~~	~~2.70~~	~~.74~~	~~2.33~~	~~8.423946~~
A	1	000	25	10	14.5	14.6	160.7	12.4	.0	1182	12.9	.90	1.99	.39	2.78	8.486514
A	1	100	25	30	15.6	15.7	181.3	12.4	15.3	1122	16.6	.94	2.53	1.93	1.23	8.526435
~~A~~	~~1~~	~~050~~	~~25~~	~~20~~	~~17.5~~	~~17.3~~	~~187.2~~	~~12.4~~	~~4.4~~	~~1124~~	~~15.6~~	~~.86~~	~~2.67~~	~~.62~~	~~2.53~~	~~8.622489~~
A	1	000	25	20	17.3	17.4	173.0	12.4	.0	1105	13.9	.81	2.49	.12	3.14	8.848565
B	1	000	25	30	16.6	16.6	138.1	9.8	.0	1075	11.5	.84	2.35	.65	2.63	8.851542
~~B~~	~~0~~	~~000~~	~~25~~	~~10~~	~~17.3~~	~~17.5~~	~~186.8~~	~~9.8~~	~~.0~~	~~1221~~	~~15.5~~	~~1.10~~	~~10.82~~	~~.87~~	~~1.45~~	~~8.929304~~
A	1	000	25	10	19.1	18.9	236.4	12.4	.0	1178	18.0	1.09	2.91	1.53	1.74	8.937590
A	1	000	25	10	15.9	15.9	172.0	12.4	.0	1168	14.1	.87	1.94	.40	2.98	8.996198
~~A~~	~~1~~	~~000~~	~~25~~	~~20~~	~~16.2~~	~~16.1~~	~~152.6~~	~~12.4~~	~~.0~~	~~1101~~	~~12.9~~	~~.76~~	~~1.89~~	~~.34~~	~~3.11~~	~~9.160151~~
A	1	100	25	10	15.2	15.8	237.6	12.4	13.5	1247	20.8	1.26	3.58	2.12	1.18	9.173673
A	1	000	25	20	14.7	14.7	139.6	12.4	.0	1105	10.7	.77	1.84	.52	3.02	9.359469
~~A~~	~~1~~	~~000~~	~~25~~	~~30~~	~~19.0~~	~~19.9~~	~~202.0~~	~~12.4~~	~~.0~~	~~1045~~	~~15.6~~	~~.82~~	~~2.63~~	~~2.04~~	~~1.48~~	~~9.449139~~
B	1	000	25	20	20.3	19.7	207.5	9.8	.0	1131	16.3	1.04	3.40	2.60	.96	9.741463
B	0	050	25	10	17.3	17.4	200.4	9.8	4.0	1244	16.5	1.18	12.09	1.31	1.24	9.851004
~~B~~	~~1~~	~~100~~	~~25~~	~~30~~	~~15.7~~	~~15.8~~	~~169.2~~	~~9.8~~	~~16.5~~	~~1129~~	~~16.7~~	~~1.10~~	~~2.89~~	~~2.62~~	~~1.05~~	~~9.865244~~
A	1	100	25	10	14.9	14.6	215.1	12.4	11.5	1252	18.3	1.16	2.75	2.40	1.33	9.987482
B	0	050	25	10	16.2	16.1	173.0	9.8	4.1	1232	14.9	1.09	10.72	1.01	1.75	9.991356
~~A~~	~~0~~	~~050~~	~~25~~	~~10~~	~~15.7~~	~~16.0~~	~~196.9~~	~~12.4~~	~~7.3~~	~~1204~~	~~17.3~~	~~1.01~~	~~9.68~~	~~1.46~~	~~1.46~~	~~10.058434~~
B	1	050	25	30	18.7	18.5	174.1	9.8	3.0	1086	14.2	.95	2.78	2.26	1.54	10.179842
A	1	000	25	20	19.4	19.4	207.9	12.4	.0	1104	16.2	.86	2.71	2.30	1.53	10.231815
~~B~~	~~1~~	~~000~~	~~25~~	~~30~~	~~18.5~~	~~18.6~~	~~162.8~~	~~9.8~~	~~.0~~	~~1072~~	~~13.3~~	~~.89~~	~~2.52~~	~~1.97~~	~~1.88~~	~~10.246955~~
B	1	100	25	20	17.8	17.7	195.6	9.8	8.8	1147	17.3	1.12	3.41	2.87	.91	10.277941
B	1	000	25	30	14.4	14.6	118.0	9.8	.0	1046	10.7	.83	1.90	.87	3.12	10.480775
~~A~~	~~1~~	~~050~~	~~25~~	~~20~~	~~19.0~~	~~19.0~~	~~214.7~~	~~12.4~~	~~3.6~~	~~1113~~	~~17.2~~	~~.91~~	~~2.64~~	~~2.77~~	~~1.18~~	~~10.482568~~
A	0	050	25	20	16.0	16.0	157.1	12.4	4.7	1129	13.7	.79	7.86	1.26	2.04	10.484935
A	1	100	25	20	17.0	16.9	209.7	12.4	9.6	1146	17.5	.99	2.99	1.87	2.26	11.099387
~~B~~	~~0~~	~~050~~	~~25~~	~~10~~	~~15.0~~	~~14.8~~	~~168.2~~	~~9.8~~	~~5.9~~	~~1247~~	~~14.7~~	~~1.14~~	~~14.29~~	~~1.26~~	~~1.56~~	~~11.176112~~
A	1	100	25	10	18.4	18.6	252.2	12.4	4.5	1173	21.0	1.11	3.11	2.79	1.39	11.194584
A	0	050	25	10	16.5	17.0	197.7	12.4	3.7	1174	17.3	.97	9.49	1.47	1.95	11.251542
~~B~~	~~1~~	~~000~~	~~25~~	~~30~~	~~20.6~~	~~20.4~~	~~204.3~~	~~9.8~~	~~.0~~	~~1062~~	~~15.9~~	~~1.01~~	~~3.15~~	~~2.98~~	~~1.33~~	~~11.519763~~
A	0	000	25	10	16.7	17.2	190.2	12.4	.0	1164	15.1	.92	8.48	.81	2.87	11.644727
B	0	000	25	10	16.2	16.1	161.6	9.8	.0	1206	13.5	1.02	10.32	1.02	2.51	11.798099
~~A~~	~~0~~	~~050~~	~~25~~	~~20~~	~~14.6~~	~~14.3~~	~~154.8~~	~~12.4~~	~~5.2~~	~~1155~~	~~13.2~~	~~.86~~	~~13.25~~	~~1.55~~	~~1.91~~	~~12.452547~~
B	1	100	25	30	18.7	18.4	190.6	9.8	6.3	1098	15.8	1.04	3.13	3.32	1.54	12.868149
B	0	100	25	10	16.2	16.1	195.8	9.8	9.8	1272	17.5	1.23	14.54	2.29	1.22	12.911836
~~A~~	~~0~~	~~000~~	~~25~~	~~20~~	~~16.2~~	~~16.0~~	~~152.6~~	~~12.4~~	~~.0~~	~~1107~~	~~12.8~~	~~.76~~	~~7.18~~	~~1.21~~	~~3.30~~	~~13.312984~~
A	0	000	25	10	15.9	16.0	172.0	12.4	.0	1167	14.1	.87	10.14	.96	3.23	13.398816
A	1	000	25	30	16.0	16.3	145.5	12.4	.0	1050	12.0	.74	2.02	.46	4.76	13.616069
~~A~~	~~1~~	~~000~~	~~25~~	~~30~~	~~14.4~~	~~14.7~~	~~133.9~~	~~12.4~~	~~.0~~	~~1058~~	~~10.9~~	~~.75~~	~~1.76~~	~~.60~~	~~4.79~~	~~13.950062~~
A	0	000	25	30	17.5	18.1	166.6	12.4	.0	1062	13.3	.77	8.84	2.28	2.35	14.035976
A	0	050	25	30	16.2	16.1	158.9	12.4	6.3	1101	13.3	.79	8.61	2.31	2.41	14.191499
~~B~~	~~0~~	~~050~~	~~25~~	~~20~~	~~15.3~~	~~14.8~~	~~151.2~~	~~9.8~~	~~7.8~~	~~1174~~	~~13.3~~	~~1.01~~	~~14.29~~	~~2.44~~	~~1.64~~	~~14.254161~~
A	0	100	25	20	16.1	15.9	184.0	12.4	11.3	1175	16.4	.92	13.30	3.08	1.14	14.273960
B	0	000	25	20	16.4	16.3	142.8	9.8	.0	1111	11.9	.88	9.99	2.07	2.55	14.362016

Table P-1 (Cont.)

B	0	050	25	20	16.5	16.3	157.0	9.8	5.3	1155	13.4	.97	11.65	2.64	1.83	14.400495
A	0	000	25	20	17.3	17.5	173.0	12.4	.0	1109	13.9	.81	8.81	1.54	3.25	14.472274
B	0	100	25	10	14.9	14.8	204.6	9.8	12.5	1304	18.6	1.39	15.15	2.86	1.27	14.606492
A	1	100	25	30	16.9	17.1	189.5	12.4	12.4	1064	17.8	.91	2.56	4.64	1.17	14.905014
A	0	050	25	20	17.6	17.3	188.1	12.4	4.5	1130	15.6	.86	11.42	2.72	2.37	15.917970
B	1	100	25	10	16.8	17.8	231.9	9.8	8.8	1197	21.7	1.40	4.04	5.51	.81	16.652260
B	0	000	25	30	16.6	16.6	138.1	9.8	.0	1075	11.5	.84	9.42	2.71	3.00	17.027403
A	0	050	25	10	15.0	14.6	178.8	12.4	5.9	1203	14.9	.96	29.69	1.99	1.66	17.736011
B	0	050	25	30	14.8	14.8	131.7	9.8	5.0	1095	11.5	.90	12.68	3.14	2.55	17.762948
B	1	050	25	20	19.8	19.2	226.1	9.8	4.5	1121	18.0	1.16	3.92	5.77	1.04	17.826112
A	1	100	25	20	19.1	19.0	232.8	12.4	6.5	1083	19.0	.99	3.21	5.80	1.14	17.940459
A	0	050	25	30	14.3	14.6	131.6	12.4	5.8	1064	12.4	.74	24.32	2.49	2.11	18.501112
A	1	050	50	10	15.0	15.4	236.3	24.7	5.7	1180	19.2	.64	1.60	.31	1.28	4.426686
A	1	100	50	10	14.9	14.6	266.1	24.7	8.9	1210	22.7	.72	1.65	.29	1.31	4.467611
B	1	100	50	30	14.9	14.6	202.7	19.7	15.1	1155	19.1	.69	1.77	.64	1.02	4.631564
A	1	100	50	20	15.1	14.6	235.8	24.7	12.5	1150	21.0	.63	1.55	.46	1.31	4.852834
B	1	100	50	10	15.7	14.6	266.3	19.7	10.6	1288	23.1	.86	2.32	.25	1.45	4.917109
B	1	100	50	20	15.9	16.0	229.9	19.7	11.5	1193	21.0	.74	2.01	.51	1.25	4.960079
B	1	100	50	10	16.4	16.2	254.9	19.7	7.5	1211	21.5	.79	2.23	.18	1.58	5.044907
B	1	100	50	10	19.0	18.7	298.6	19.7	.7	1232	22.4	.80	2.31	.36	1.61	5.582461
B	1	050	50	20	20.0	17.7	261.8	19.7	4.5	1143	19.7	.67	2.34	.47	1.52	5.634577
B	1	000	50	10	19.0	18.8	294.0	19.7	.0	1258	22.7	.79	2.28	.41	1.59	5.645588
A	1	100	50	20	15.6	15.8	273.9	24.7	13.4	1173	23.2	.71	1.91	.84	1.27	5.785545
A	1	100	50	30	15.1	14.6	218.9	24.7	13.4	1115	19.4	.59	1.44	.51	1.65	5.792432
B	1	100	50	20	14.7	14.6	250.4	19.7	16.9	1237	23.5	.86	2.31	1.14	.97	5.864900
B	1	000	50	20	19.5	19.0	271.2	19.7	.0	1134	21.7	.71	2.10	.91	1.25	5.962159
B	1	050	50	20	14.9	14.6	193.5	19.7	9.0	1157	17.9	.66	1.69	.36	1.84	5.975108
B	1	100	50	10	17.5	17.1	260.3	19.7	4.0	1227	21.3	.77	2.32	.21	1.96	6.094548
A	1	050	50	10	13.7	14.6	210.6	24.7	4.4	1130	18.0	.62	1.47	.29	1.99	6.114670
B	1	100	50	20	17.5	17.5	270.9	19.7	10.0	1178	23.2	.79	2.42	1.14	1.05	6.117253
B	1	100	50	30	16.0	16.1	229.4	19.7	14.7	1141	21.0	.73	2.07	1.21	1.25	6.685043
A	1	000	50	10	15.2	15.4	227.5	24.7	.0	1172	17.6	.61	1.54	.30	2.25	6.809648
B	1	100	50	20	19.6	19.0	291.8	19.7	2.5	1144	23.4	.76	2.39	1.59	.90	6.830990
B	1	000	50	30	20.6	20.5	259.8	19.7	.0	1070	20.3	.64	2.06	1.14	1.40	6.886370
A	1	100	50	10	15.0	15.4	273.9	24.7	9.9	1222	23.2	.74	1.95	.46	2.11	6.970481
B	1	050	50	10	15.2	14.6	216.2	19.7	6.0	1223	18.1	.72	1.89	.26	2.43	7.265029
B	1	100	50	30	18.4	18.4	255.3	19.7	8.3	1111	23.3	.71	2.04	1.33	1.38	7.293902
B	1	000	50	20	17.8	17.8	220.8	19.7	.0	1109	17.8	.63	1.92	.35	2.47	7.593364
B	1	000	50	10	17.3	17.3	239.0	19.7	.0	1188	19.3	.70	2.08	.22	2.59	7.623350
B	1	050	50	30	18.4	18.1	221.1	19.7	3.9	1084	18.2	.61	1.71	.54	2.39	7.795014
B	0	100	50	10	15.7	14.8	266.3	19.7	10.8	1289	23.1	.86	8.30	.89	1.29	7.836908
B	1	050	50	20	15.7	15.8	193.5	19.7	3.9	1130	17.1	.63	1.70	.29	2.67	7.882317
B	0	100	50	10	16.4	16.1	254.9	19.7	7.5	1255	21.5	.79	7.42	.78	1.59	8.059792
A	1	050	50	20	15.9	16.0	223.1	24.7	7.0	1118	19.0	.57	1.47	.33	2.76	8.137231
B	1	050	50	30	16.7	16.5	193.5	19.7	6.6	1080	17.2	.59	1.78	.42	2.67	8.222920
A	1	100	50	30	16.2	16.2	231.5	24.7	10.4	1090	20.4	.58	1.44	.45	2.72	8.321094
B	1	050	50	10	15.9	15.7	225.3	19.7	3.9	1211	18.7	.72	1.98	.17	2.98	8.446987
B	1	000	50	30	18.5	18.4	214.3	19.7	.0	1069	17.4	.59	1.66	.44	2.89	8.786406
A	1	100	50	20	17.8	17.8	269.5	24.7	5.5	1119	22.2	.61	1.76	.62	2.73	8.854842
B	0	100	50	10	18.9	18.7	298.6	19.7	.7	1233	22.3	.80	8.90	1.11	1.44	8.924964
B	0	100	50	10	17.5	17.0	266.3	19.7	4.1	1229	21.3	.77	7.72	.75	1.96	8.999857
B	0	000	50	10	19.0	18.8	294.0	19.7	.0	1260	22.7	.79	8.97	1.19	1.47	9.215674
A	1	050	50	20	15.1	14.6	213.3	24.7	5.4	1112	17.8	.57	1.40	.39	3.23	9.437984
B	1	050	50	30	14.4	14.6	168.6	19.7	5.8	1103	14.8	.59	1.47	.49	3.30	9.877475
A	1	050	50	30	15.0	14.6	191.6	24.7	6.1	1054	17.0	.52	1.26	.47	3.43	10.091930
B	0	050	50	10	15.9	16.0	225.3	19.7	3.9	1216	18.7	.72	6.56	.66	2.67	10.214168
A	1	100	50	30	18.0	17.9	259.1	24.7	8.0	1074	21.9	.58	1.60	.96	3.03	10.387052
A	1	100	50	10	16.1	16.1	259.5	24.7	3.6	1184	21.0	.65	1.71	.16	3.85	10.518185
B	1	000	50	10	15.9	16.1	211.7	19.7	.0	1184	17.4	.68	1.85	.17	3.95	10.833752
B	0	050	50	20	14.9	14.8	193.5	19.7	9.1	1157	17.9	.66	6.31	1.70	1.95	10.877224

Table P-1 (Cont.)

B	0	000	50	10	17.3	17.3	239.0	19.7	.0	1188	19.3	.70	6.93	.75	2.82	10.917504
B	0	050	50	20	20.0	17.8	261.8	19.7	4.6	1145	19.7	.67	9.67	1.98	1.42	11.223386
~~B~~	~~1~~	~~000~~	~~50~~	~~10~~	~~14.6~~	~~14.6~~	~~188.9~~	~~19.7~~	~~.0~~	~~1186~~	~~15.9~~	~~.66~~	~~1.70~~	~~.39~~	~~3.96~~	~~11.351220~~
B	0	050	50	10	15.2	14.8	216.2	19.7	6.0	1227	18.1	.72	8.01	1.06	2.77	11.866248
A	1	050	50	30	18.1	18.1	245.9	24.7	4.2	1062	20.0	.55	1.52	,45	4.19	12.019620
~~B~~	~~0~~	~~000~~	~~50~~	~~20~~	~~17.8~~	~~17.7~~	~~220.8~~	~~19.7~~	~~.0~~	~~0969~~	~~17.8~~	~~.63~~	~~7.27~~	~~1.44~~	~~2.60~~	~~12.150430~~
B	0	100	50	20	15.9	16.0	229.9	19.7	11.7	1193	21.0	.74	10.01	2.75	1.07	12.326435
B	0	050	50	20	15.7	15.8	193.5	19.7	3.9	1133	17.1	.63	6.23	1.44	2.86	12.494548
~~A~~	~~0~~	~~050~~	~~50~~	~~20~~	~~15.9~~	~~16.0~~	~~223.1~~	~~24.7~~	~~7.1~~	~~1119~~	~~19.0~~	~~.57~~	~~5.88~~	~~1.45~~	~~2.93~~	~~12.590997~~
A	1	000	50	10	14.6	14.6	226.2	24.7	.0	1160	17.2	.63	1.53	.34	4.61	12.804268
B	0	100	50	30	15.0	14.8	202.7	19.7	15.4	1157	19.1	.69	8.08	3.27	1.02	12.902080
~~A~~	~~0~~	~~050~~	~~50~~	~~10~~	~~15.0~~	~~15.3~~	~~236.3~~	~~24.7~~	~~5.8~~	~~1179~~	~~19.2~~	~~.64~~	~~22.20~~	~~1.14~~	~~1.46~~	~~12.959000~~
A	1	000	50	20	17.9	17.9	245.2	24.7	.0	1090	18.8	.55	1.47	.27	4.82	13.140890
B	1	100	50	30	20.4	20.3	298.6	19.7	4.3	1073	23.4	.74	2.44	4.14	1.03	13.390208
~~A~~	~~0~~	~~000~~	~~50~~	~~10~~	~~15.2~~	~~15.4~~	~~227.5~~	~~24.7~~	~~.0~~	~~1173~~	~~17.6~~	~~.61~~	~~16.78~~	~~1.10~~	~~2.38~~	~~13.568221~~
B	1	000	50	20	15.8	16.0	184.4	19.7	.0	1112	15.3	.59	1.66	.32	5.02	13.818723
B	0	050	50	30	16.7	16.5	193.5	19.7	6.7	1081	17.2	.59	5.90	2.10	2.85	13.982245
~~A~~	~~1~~	~~000~~	~~50~~	~~10~~	~~16.2~~	~~16.5~~	~~246.2~~	~~24.7~~	~~.0~~	~~1157~~	~~19.2~~	~~.61~~	~~1.66~~	~~.19~~	~~5.24~~	~~14.051650~~
B	1	000	50	20	14.3	14.6	170.7	19.7	.0	1118	14.3	.60	1.57	.46	5.04	14.183716
B	0	000	50	10	15.9	16.1	211.7	19.7	.0	1186	17.4	.68	6.16	.69	4.36	14.394692
~~A~~	~~1~~	~~000~~	~~50~~	~~10~~	~~17.6~~	~~17.3~~	~~284.5~~	~~24.7~~	~~.0~~	~~1186~~	~~20.7~~	~~.64~~	~~1.73~~	~~.34~~	~~5.27~~	~~14.513092~~
A	0	100	50	10	16.1	16.2	259.5	24.7	3.7	1181	21.0	.65	8.10	.87	4.01	14.529304
B	0	050	50	30	18.4	18.2	221.1	19.7	4.0	1086	18.2	.61	7.38	2.62	2.39	14.535832
~~A~~	~~0~~	~~100~~	~~50~~	~~30~~	~~18.0~~	~~18.2~~	~~259.1~~	~~24.7~~	~~8.1~~	~~1073~~	~~22.0~~	~~.58~~	~~7.60~~	~~1.96~~	~~3.02~~	~~14.565782~~
B	0	000	50	30	18.5	18.5	214.3	19.7	.0	1071	17.3	.59	6.29	2.09	3.06	14.597561
A	1	100	50	10	17.4	17.1	280.5	24.7	.2	1179	20.6	.65	1.74	.31	5.49	14.992862
~~A~~	~~1~~	~~050~~	~~50~~	~~30~~	~~16.2~~	~~16.3~~	~~215.9~~	~~24.7~~	~~5.0~~	~~1069~~	~~17.9~~	~~.54~~	~~1.34~~	~~.34~~	~~5.80~~	~~15.723386~~
A	0	100	50	30	15.1	15.0	218.9	24.7	13.7	1119	19.5	.59	16.16	2.87	1.69	15.977941
A	0	100	50	30	16.2	16.2	231.5	24.7	10.6	1089	20.1	.58	8.36	2.91	2.79	16.531385
~~A~~	~~1~~	~~000~~	~~50~~	~~20~~	~~14.6~~	~~14.6~~	~~202.9~~	~~24.7~~	~~.0~~	~~1106~~	~~16.0~~	~~.56~~	~~1.34~~	~~.45~~	~~6.15~~	~~16.866679~~
B	0	000	50	20	19.5	19.0	271.2	19.7	.0	1135	21.6	.71	11.19	4.72	.94	17.153372
A	0	100	50	10	14.9	14.7	266.1	24.7	9.5	1207	22.7	.72	38.50	1.24	1.15	17.222920
~~A~~	~~1~~	~~000~~	~~50~~	~~30~~	~~20.2~~	~~16.6~~	~~290.7~~	~~24.7~~	~~.0~~	~~1043~~	~~22.1~~	~~.58~~	~~1.80~~	~~1.76~~	~~4.98~~	~~17.272095~~
B	1	000	50	30	14.4	14.6	168.6	19.7	.0	1087	13.6	.59	1.47	.59	6.22	17.421377
A	0	000	50	20	17.9	17.8	245.2	24.7	.0	1093	18.8	.55	5.64	1.18	5.20	17.536872
~~A~~	~~0~~	~~100~~	~~50~~	~~20~~	~~17.8~~	~~17.8~~	~~269.5~~	~~24.7~~	~~5.7~~	~~1117~~	~~22.2~~	~~.61~~	~~8.16~~	~~3.44~~	~~2.73~~	~~17.615244~~
A	0	050	50	20	15.1	15.0	213.3	24.7	5.7	1119	17.7	.57	15.70	1.66	3.75	18.041428
A	0	000	50	10	16.2	16.5	246.2	24.7	.0	1159	19.2	.61	7.03	.75	5.66	18.046915
~~A~~	~~0~~	~~100~~	~~50~~	~~20~~	~~15.1~~	~~14.8~~	~~235.8~~	~~24.7~~	~~13.1~~	~~1150~~	~~21.1~~	~~.63~~	~~29.69~~	~~2.63~~	~~1.16~~	~~18.046987~~
A	1	100	50	20	19.6	19.4	307.7	24.7	.0	1099	23.1	.63	2.01	1.28	5.74	18.063128
B	0	050	50	30	14.4	14.8	168.6	19.7	6.0	1103	14.8	.59	11.10	2.36	3.63	18.095803
~~A~~	~~0~~	~~100~~	~~50~~	~~10~~	~~15.0~~	~~15.3~~	~~273.9~~	~~24.7~~	~~19.2~~	~~1225~~	~~23.2~~	~~.74~~	~~28.27~~	~~1.68~~	~~2.28~~	~~18.112267~~
A	0	000	50	10	17.6	17.3	280.5	24.7	.0	1183	20.5	.64	7.10	1.04	5.53	18.449821
B	1	100	90	20	14.8	14.7	293.8	35.3	12.9	1203	25.9	.56	1.35	.32	1.78	5.627547
~~B~~	~~1~~	~~100~~	~~90~~	~~30~~	~~14.8~~	~~14.8~~	~~261.9~~	~~35.3~~	~~14.8~~	~~1142~~	~~24.3~~	~~.50~~	~~1.28~~	~~.38~~	~~1.93~~	~~6.128304~~
B	1	100	90	20	17.1	17.2	331.8	35.3	8.4	1180	27.0	.55	1.53	.39	2.29	7.126220
B	1	100	90	20	18.8	19.0	350.8	35.3	1.3	1040	26.3	.53	1.65	.27	2.64	7.743831
~~B~~	~~1~~	~~100~~	~~90~~	~~20~~	~~15.9~~	~~15.8~~	~~323.4~~	~~35.3~~	~~9.8~~	~~1193~~	~~26.5~~	~~.58~~	~~1.58~~	~~.25~~	~~2.67~~	~~7.749462~~
B	1	100	90	10	15.2	14.7	322.5	35.3	9.1	1263	26.3	.60	1.49	.29	2.72	7.945552
B	1	100	90	30	19.0	19.2	325.7	35.3	4.4	1092	26.1	.48	1.53	.39	2.73	8.226220
~~B~~	~~1~~	~~000~~	~~90~~	~~20~~	~~18.4~~	~~18.7~~	~~332.6~~	~~35.3~~	~~.0~~	~~1137~~	~~25.3~~	~~.51~~	~~1.57~~	~~.23~~	~~3.22~~	~~9.972740~~
B	1	100	90	10	15.9	16.0	322.5	35.3	6.3	1243	26.2	.58	1.40	.19	3.43	9.450179
B	0	100	90	30	14.8	14.9	261.9	35.3	15.0	1139	24.2	.50	4.24	1.79	1.98	10.562912
~~B~~	~~1~~	~~100~~	~~90~~	~~30~~	~~15.9~~	~~15.8~~	~~277.9~~	~~35.3~~	~~13.5~~	~~1120~~	~~23.4~~	~~.50~~	~~1.36~~	~~.29~~	~~3.86~~	~~10.757317~~
B	1	100	90	30	17.8	17.7	316.6	35.3	6.6	1105	22.0	.50	1.50	.29	3.96	11.048494
B	1	000	90	30	19.3	19.2	305.2	35.3	.0	1064	24.3	.45	1.40	.30	4.00	11.143472
~~B~~	~~1~~	~~100~~	~~90~~	~~10~~	~~17.4~~	~~17.4~~	~~350.8~~	~~35.3~~	~~1.1~~	~~1222~~	~~26.3~~	~~.57~~	~~1.66~~	~~.14~~	~~4.16~~	~~11.229699~~
B	1	050	90	20	17.0	17.1	300.0	35.3	4.2	1137	24.0	.50	1.30	.28	4.15	11.440280
B	0	100	90	20	17.1	17.1	331.8	35.3	8.4	1179	27.0	.55	6.54	1.68	2.22	11.571090

Table P-1 (Cont.)

~~B~~	~~0~~	~~100~~	~~90~~	~~20~~	~~15.9~~	~~15.8~~	~~323.4~~	~~35.3~~	~~9.9~~	~~1193~~	~~26.5~~	~~.58~~	~~5.98~~	~~1.44~~	~~2.80~~	~~11.771019~~
B	1	050	90	10	14.9	14.7	281.6	35.3	4.6	1221	23.3	.54	1.30	.31	4.26	11.788451
B	0	100	90	10	15.2	14.8	322.5	35.3	9.2	1273	26.3	.60	8.49	1.18	2.65	12.000108
~~A~~	~~0~~	~~100~~	~~90~~	~~20~~	~~18.8~~	~~18.8~~	~~350.8~~	~~35.3~~	~~1.3~~	~~1041~~	~~26.2~~	~~.53~~	~~6.43~~	~~1.48~~	~~2.64~~	~~12.100933~~
B	0	100	90	10	15.9	16.0	322.5	35.3	6.4	1244	26.2	.58	5.24	.84	3.43	12.164957
B	1	000	90	10	17.5	17.5	343.9	35.3	.0	1215	26.0	.56	1.63	.16	4.53	12.194656
~~B~~	~~0~~	~~100~~	~~90~~	~~20~~	~~14.8~~	~~14.7~~	~~293.8~~	~~35.3~~	~~13.2~~	~~1203~~	~~25.7~~	~~.56~~	~~13.25~~	~~1.64~~	~~1.78~~	~~12.347459~~
B	0	000	90	20	18.4	18.7	332.6	35.3	.0	1139	25.1	.51	5.88	1.12	3.25	12.586119
B	1	050	90	20	14.5	14.7	264.2	35.3	6.1	1167	22.2	.52	1.08	.34	4.81	13.171915
~~B~~	~~0~~	~~100~~	~~90~~	~~30~~	~~19.0~~	~~19.1~~	~~325.7~~	~~35.3~~	~~4.5~~	~~1092~~	~~26.1~~	~~.48~~	~~5.75~~	~~2.09~~	~~2.80~~	~~13.788737~~
B	0	100	90	10	17.4	17.4	350.8	35.3	1.1	1221	26.3	.57	5.48	.55	4.39	13.928228
B	1	050	90	30	14.7	14.8	239.2	35.3	7.1	1110	20.6	.46	1.17	.44	5.31	14.692288
~~A~~	~~0~~	~~000~~	~~90~~	~~10~~	~~17.5~~	~~17.4~~	~~343.9~~	~~35.3~~	~~.0~~	~~1218~~	~~25.8~~	~~.56~~	~~5.47~~	~~.57~~	~~4.71~~	~~14.774067~~
A	1	100	90	20	15.7	14.8	320.2	39.6	4.2	1124	25.2	.52	1.47	.35	5.49	15.011011
B	1	050	90	20	15.9	15.8	268.8	35.3	4.1	1138	22.4	.48	1.28	.25	5.72	15.286227
~~B~~	~~0~~	~~100~~	~~90~~	~~30~~	~~15.9~~	~~15.9~~	~~277.9~~	~~35.3~~	~~13.7~~	~~1119~~	~~23.4~~	~~.50~~	~~4.15~~	~~1.69~~	~~3.98~~	~~15.292539~~
B	1	050	90	10	16.5	15.9	311.1	35.3	3.1	1215	23.3	.53	1.36	.20	5.80	15.387805
B	0	100	90	30	17.8	17.6	316.6	35.3	6.6	1108	22.0	.50	5.28	1.69	3.96	15.574892
~~B~~	~~0~~	~~050~~	~~90~~	~~20~~	~~17.0~~	~~17.1~~	~~300.0~~	~~35.3~~	~~4.3~~	~~1138~~	~~24.0~~	~~.50~~	~~5.13~~	~~1.19~~	~~4.54~~	~~15.761263~~
B	0	000	90	30	19.3	19.2	305.2	35.3	.0	1022	24.4	.45	4.79	1.57	4.33	16.063092
B	1	050	90	30	17.5	17.4	277.9	35.3	3.2	1071	22.4	.45	1.31	.28	6.27	16.743221
~~A~~	~~1~~	~~100~~	~~90~~	~~30~~	~~15.8~~	~~14.9~~	~~310.5~~	~~39.6~~	~~8.9~~	~~1092~~	~~25.3~~	~~.49~~	~~1.43~~	~~.47~~	~~6.13~~	~~16.891930~~
A	1	100	90	30	15.8	15.0	306.7	39.6	8.3	1089	24.9	.49	1.40	.43	6.33	17.285545
B	0	050	90	10	16.5	16.0	311.1	35.3	3.2	1227	23.3	.53	5.75	.85	6.00	18.764347
~~A~~	~~1~~	~~100~~	~~90~~	~~10~~	~~15.4~~	~~15.5~~	~~343.0~~	~~39.6~~	~~1.5~~	~~1191~~	~~25.7~~	~~.56~~	~~1.57~~	~~.24~~	~~7.11~~	~~18.822131~~

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Table P-2

COMPUTER-SORTED SPEED, PERCENT POWER, AND TOTAL WEIGHTED EMISSION DATA – 1,600 RPM, ENGINES A AND B (PRINTED FOR SCR < 12)

E	C	RR	PP	ST	MAFR	CAFR	IAR	PO	ER	ET	MP	SFC	CO	HC	NO	SCR
B	1	050	10	10	14.8	14.6	183.5	5.4	6.0	1329	12.4	2.28	5.80	.42	2.06	7.880273
~~B~~	~~1~~	~~050~~	~~10~~	~~20~~	~~14.8~~	~~14.7~~	~~164.2~~	~~5.4~~	~~6.0~~	~~1265~~	~~11.5~~	~~2.04~~	~~5.47~~	~~1.11~~	~~1.84~~	~~8.916141~~
A	1	050	10	20	15.4	14.9	160.1	5.3	5.9	1280	10.8	1.95	4.33	.90	2.29	9.193651
B	1	000	10	30	14.0	14.6	126.0	5.4	.0	1120	8.6	1.65	4.09	1.01	2.48	9.866356
~~B~~	~~1~~	~~050~~	~~10~~	~~20~~	~~16.9~~	~~16.9~~	~~188.1~~	~~5.4~~	~~3.8~~	~~1239~~	~~11.9~~	~~2.04~~	~~5.62~~	~~1.27~~	~~2.11~~	~~10.025502~~
B	1	000	10	20	14.4	14.7	143.9	5.4	.0	1215	9.5	1.84	4.80	1.31	2.22	10.156887
A	1	050	10	10	14.9	14.8	177.9	5.3	5.1	1354	11.4	2.24	5.13	.46	3.06	10.280775
~~B~~	~~1~~	~~000~~	~~10~~	~~10~~	~~14.7~~	~~14.6~~	~~165.8~~	~~5.4~~	~~.0~~	~~1287~~	~~10.6~~	~~2.08~~	~~5.24~~	~~.63~~	~~2.91~~	~~10.352762~~
A	1	000	10	30	14.4	14.8	125.0	5.3	.0	1138	8.6	1.64	3.49	.97	2.87	10.567324
A	1	050	10	10	16.0	16.0	195.2	5.3	4.8	1348	12.6	2.29	5.13	.76	2.95	10.737482
~~A~~	~~1~~	~~100~~	~~10~~	~~10~~	~~15.3~~	~~14.8~~	~~214.7~~	~~5.3~~	~~11.1~~	~~1391~~	~~14.1~~	~~2.63~~	~~6.19~~	~~1.21~~	~~2.47~~	~~10.946808~~
A	1	050	10	20	16.9	16.5	168.6	5.3	4.8	1260	11.1	1.88	4.57	1.46	2.42	10.955093
A	1	000	10	20	16.5	16.5	160.1	5.3	.0	1240	10.2	1.82	4.20	.69	3.22	10.968221
~~B~~	~~1~~	~~050~~	~~10~~	~~10~~	~~16.9~~	~~16.1~~	~~199.7~~	~~5.4~~	~~3.4~~	~~1322~~	~~13.1~~	~~2.30~~	~~5.81~~	~~1.10~~	~~2.67~~	~~11.066750~~
B	1	000	10	30	16.6	16.9	152.4	5.4	.0	1160	9.7	1.69	4.42	1.16	2.78	11.079268
B	1	000	10	20	16.7	17.0	176.9	5.4	.0	1230	11.2	1.95	5.13	.90	2.98	11.153945
~~A~~	~~1~~	~~000~~	~~10~~	~~10~~	~~16.2~~	~~16.0~~	~~180.0~~	~~5.3~~	~~.0~~	~~1318~~	~~11.2~~	~~2.09~~	~~4.88~~	~~.58~~	~~3.62~~	~~11.899028~~
A	1	050	25	20	14.6	14.7	210.2	13.4	9.8	1306	14.1	1.07	2.61	.36	1.25	4.770696
B	1	100	25	10	15.2	14.7	287.4	13.6	11.9	1357	19.3	1.39	3.72	.34	1.37	5.348386
~~B~~	~~1~~	~~100~~	~~25~~	~~10~~	~~16.2~~	~~16.2~~	~~302.2~~	~~13.6~~	~~10.3~~	~~1356~~	~~19.4~~	~~1.36~~	~~3.92~~	~~.33~~	~~1.36~~	~~5.357819~~
B	1	050	25	10	14.9	14.7	231.7	13.6	5.0	1272	14.9	1.14	3.00	.21	1.62	5.444548
B	1	050	25	20	14.9	14.7	196.7	13.6	6.5	1230	13.3	.97	2.48	.33	1.65	5.659200
~~B~~	~~1~~	~~100~~	~~25~~	~~10~~	~~17.7~~	~~17.6~~	~~318.8~~	~~13.6~~	~~6.6~~	~~1320~~	~~20.0~~	~~1.32~~	~~4.12~~	~~.38~~	~~1.42~~	~~5.688594~~
A	1	050	25	30	14.8	14.6	195.0	13.4	12.0	1255	13.4	.98	.20	.97	1.33	5.749677
B	1	050	25	30	15.1	14.6	191.6	13.6	9.0	1196	12.7	.93	2.41	.50	1.61	5.953336
~~A~~	~~1~~	~~100~~	~~25~~	~~20~~	~~16.3~~	~~16.3~~	~~233.8~~	~~13.4~~	~~9.5~~	~~1272~~	~~15.0~~	~~1.06~~	~~2.91~~	~~.48~~	~~1.60~~	~~6.026614~~
A	1	100	25	30	16.4	16.7	236.4	13.2	15.0	1188	15.9	1.09	2.99	.82	1.29	6.104412
B	1	100	25	20	15.0	14.7	253.6	13.6	15.9	1269	17.8	1.24	3.37	.94	1.14	6.133859
~~B~~	~~1~~	~~050~~	~~25~~	~~10~~	~~16.1~~	~~16.1~~	~~253.3~~	~~13.6~~	~~5.5~~	~~1275~~	~~16.3~~	~~1.15~~	~~3.29~~	~~.17~~	~~1.90~~	~~6.357281~~
B	1	050	25	10	17.5	17.4	283.4	13.6	3.0	1271	16.9	1.19	3.66	.17	1.98	6.441105
B	1	050	25	20	16.7	16.4	239.3	13.6	7.6	1245	15.4	1.05	3.10	.46	1.81	6.558716
~~B~~	~~1~~	~~000~~	~~25~~	~~10~~	~~17.7~~	~~17.6~~	~~268.9~~	~~13.6~~	~~.0~~	~~1224~~	~~16.0~~	~~1.12~~	~~3.47~~	~~.16~~	~~2.10~~	~~6.660832~~
A	1	050	25	20	18.5	18.3	250.4	13.2	3.7	1239	14.5	1.02	3.06	.95	1.44	6.817073
A	1	100	25	10	17.0	16.8	272.1	13.4	5.4	1325	16.3	1.19	3.39	.42	1.93	6.846449
~~A~~	~~1~~	~~000~~	~~25~~	~~20~~	~~18.6~~	~~18.3~~	~~241.7~~	~~13.2~~	~~.0~~	~~1235~~	~~14.2~~	~~.98~~	~~3.04~~	~~.67~~	~~1.73~~	~~6.853264~~
A	1	100	25	10	14.9	14.7	306.6	13.4	14.9	1408	20.5	1.53	4.14	1.15	1.22	7.072525
B	1	100	25	10	19.4	18.9	343.5	13.6	2.4	1316	20.7	1.30	4.30	.86	1.53	7.187267
~~B~~	~~1~~	~~050~~	~~25~~	~~20~~	~~18.4~~	~~18.1~~	~~269.0~~	~~13.6~~	~~5.2~~	~~1209~~	~~16.6~~	~~1.07~~	~~3.56~~	~~1.17~~	~~1.38~~	~~7.350717~~
B	1	000	25	20	18.5	18.4	251.3	13.6	.0	1215	14.5	1.00	3.24	.76	1.82	7.356600
A	1	050	25	10	14.8	14.7	229.2	13.4	7.3	1349	14.5	1.15	2.93	.33	2.28	7.366643
~~B~~	~~1~~	~~050~~	~~25~~	~~30~~	~~16.2~~	~~16.6~~	~~221.4~~	~~13.6~~	~~8.9~~	~~1108~~	~~14.7~~	~~1.00~~	~~2.87~~	~~1.05~~	~~1.61~~	~~7.430093~~
A	1	100	25	20	14.3	14.6	257.8	13.4	17.7	1330	18.6	1.34	3.30	1.77	.95	7.662661
B	1	000	25	10	19.7	19.2	348.0	13.6	.0	1311	19.2	1.30	4.36	.82	1.78	7.732353
~~A~~	~~1~~	~~050~~	~~25~~	~~20~~	~~16.6~~	~~16.4~~	~~212.0~~	~~13.2~~	~~4.4~~	~~1260~~	~~13.2~~	~~.97~~	~~2.68~~	~~.24~~	~~2.57~~	~~7.798601~~
A	1	100	25	10	17.2	15.7	287.4	13.2	9.7	1302	16.6	1.26	3.63	.30	2.49	8.024354
B	1	000	25	10	14.8	14.7	205.8	13.6	.0	1289	13.3	1.02	2.59	.28	2.65	8.069692
~~A~~	~~1~~	~~100~~	~~25~~	~~10~~	~~18.0~~	~~18.3~~	~~298.4~~	~~13.2~~	~~1.4~~	~~1349~~	~~16.9~~	~~1.25~~	~~4.00~~	~~.99~~	~~1.87~~	~~8.266105~~
A	1	000	25	10	16.9	16.8	241.6	13.2	.0	1295	14.3	1.08	3.05	.35	2.65	8.375717
A	1	000	25	10	13.7	14.6	195.8	13.4	.0	1329	12.1	1.06	2.50	.30	2.78	8.417001
~~B~~	~~0~~	~~050~~	~~25~~	~~10~~	~~17.6~~	~~17.4~~	~~283.4~~	~~13.6~~	~~3.0~~	~~1267~~	~~16.8~~	~~1.18~~	~~9.54~~	~~.62~~	~~1.66~~	~~8.468077~~
B	1	000	25	10	16.4	16.2	234.2	13.6	.0	1267	13.9	1.05	3.12	.14	2.89	8.484110
B	1	000	25	30	18.8	18.6	236.8	13.6	.0	1145	14.1	.92	2.97	1.23	1.85	8.498529
~~B~~	~~0~~	~~050~~	~~25~~	~~10~~	~~16.1~~	~~16.1~~	~~253.3~~	~~13.6~~	~~5.5~~	~~1300~~	~~16.3~~	~~1.15~~	~~8.04~~	~~.49~~	~~1.99~~	~~8.534828~~
B	0	000	25	10	17.7	17.6	268.9	13.6	.0	1226	16.0	1.12	8.50	.38	2.10	8.676829
A	1	000	25	20	13.7	14.7	174.0	13.4	.0	1259	11.1	.94	2.17	.41	2.87	8.813235

Table P-2 (Cont.)

B	1	100	25	30	14.9	14.6	229.9	13.6	18.1	1221	16.1	1.13	2.90	2.21	1.03	8.818185
A	1	000	25	10	15.6	15.8	209.2	13.2	.0	1306	12.5	1.01	2.42	.12	3.13	8.829448
~~A~~	~~1~~	~~000~~	~~25~~	~~30~~	~~20.8~~	~~18.6~~	~~243.2~~	~~13.2~~	~~.0~~	~~1171~~	~~13.0~~	~~.88~~	~~3.14~~	~~.97~~	~~2.23~~	~~8.864383~~
A	1	000	25	10	17.9	18.1	284.0	13.2	.0	1326	17.1	1.20	3.57	1.13	2.04	8.906098
A	1	000	25	30	17.4	17.6	196.7	13.2	.0	1164	12.8	.85	2.41	.36	2.94	8.936872
~~B~~	~~0~~	~~100~~	~~25~~	~~10~~	~~15.2~~	~~14.9~~	~~287.4~~	~~13.6~~	~~11.7~~	~~1354~~	~~19.3~~	~~1.39~~	~~10.76~~	~~1.11~~	~~1.29~~	~~9.097023~~
A	0	050	25	20	14.6	14.8	210.2	13.4	9.8	1317	14.1	1.07	11.40	1.19	1.25	9.380380
B	0	050	25	10	14.9	14.9	231.7	13.6	5.1	1272	14.9	1.14	12.07	.55	1.81	9.416463
~~A~~	~~1~~	~~100~~	~~25~~	~~20~~	~~18.2~~	~~18.1~~	~~274.4~~	~~13.4~~	~~7.1~~	~~1233~~	~~16.3~~	~~1.12~~	~~3.49~~	~~2.34~~	~~1.09~~	~~9.458780~~
A	1	050	25	30	18.9	17.4	240.4	13.2	6.8	1203	13.9	.96	2.95	.87	2.63	9.564598
B	1	000	25	20	17.1	16.5	207.2	13.6	.0	1184	12.6	.89	2.76	.35	3.25	9.790423
~~A~~	~~1~~	~~050~~	~~25~~	~~10~~	~~15.9~~	~~15.8~~	~~231.3~~	~~13.2~~	~~4.8~~	~~1323~~	~~14.3~~	~~1.10~~	~~3.00~~	~~.11~~	~~3.60~~	~~10.150646~~
B	1	050	25	30	18.6	18.4	256.7	13.6	5.2	1150	16.5	1.01	3.31	2.24	1.50	10.186944
B	1	100	25	20	16.3	15.8	293.0	13.6	15.1	1272	19.4	1.32	3.91	2.38	1.32	10.254878
~~B~~	~~1~~	~~000~~	~~25~~	~~20~~	~~14.9~~	~~14.7~~	~~180.9~~	~~13.6~~	~~.0~~	~~1199~~	~~11.2~~	~~.89~~	~~2.40~~	~~.50~~	[illegible]	~~10.275395~~
A	0	000	25	10	16.9	16.8	241.6	13.2	.0	1299	14.3	1.08	8.05	.57	2.65	10.382891
B	1	000	25	30	17.0	16.7	197.1	13.6	.0	1144	11.9	.85	2.48	.53	3.36	10.422095
~~A~~	~~1~~	~~000~~	~~25~~	~~30~~	~~13.7~~	~~14.6~~	~~153.8~~	~~13.4~~	~~.0~~	~~1180~~	~~10.5~~	~~.83~~	~~1.81~~	~~.58~~	~~3.41~~	~~10.471987~~
B	0	050	25	20	16.7	16.4	239.3	13.6	7.7	1296	15.4	1.05	11.27	1.33	1.68	10.758608
B	0	000	25	10	16.4	16.2	234.2	13.6	.0	1269	13.9	1.05	7.36	.36	3.09	10.767755
~~A~~	~~1~~	~~000~~	~~25~~	~~20~~	~~16.2~~	~~16.4~~	~~197.4~~	~~13.2~~	~~.0~~	~~1236~~	~~11.7~~	~~.92~~	~~2.50~~	~~.26~~	~~3.76~~	~~10.769449~~
B	1	050	25	20	19.5	19.4	295.7	13.6	2.9	1202	17.3	1.12	3.90	2.77	1.15	10.778156
B	0	100	25	10	16.3	16.1	302.2	13.6	10.3	1355	19.5	1.36	12.28	1.79	1.19	10.952618
~~B~~	~~0~~	~~050~~	~~25~~	~~20~~	~~14.9~~	~~14.8~~	~~196.7~~	~~13.6~~	~~6.6~~	~~1239~~	~~13.3~~	~~.97~~	~~12.06~~	~~1.09~~	~~1.93~~	~~11.030595~~
B	1	000	25	30	14.6	14.6	168.0	13.6	.0	1149	10.6	.84	2.12	.60	3.67	11.261944
A	0	050	25	20	16.6	16.4	212.0	13.2	4.5	1265	13.2	.97	9.46	.88	2.57	11.353694
~~A~~	~~0~~	~~000~~	~~25~~	~~10~~	~~15.6~~	~~15.7~~	~~209.2~~	~~13.2~~	~~.0~~	~~1316~~	~~12.5~~	~~1.01~~	~~7.63~~	~~.30~~	~~3.38~~	~~11.425825~~
A	0	050	25	10	15.9	15.3	231.3	13.2	4.8	1328	14.3	1.10	8.84	.34	3.26	11.579268
B	0	050	25	30	15.1	14.8	191.6	13.6	9.1	1198	12.7	.93	11.29	1.68	1.72	11.718149
~~B~~	~~0~~	~~000~~	~~25~~	~~20~~	~~18.5~~	~~18.4~~	~~251.3~~	~~13.6~~	~~.0~~	~~1214~~	~~14.5~~	~~1.00~~	~~11.75~~	~~1.94~~	~~1.47~~	~~11.862590~~
B	0	100	25	10	17.8	17.5	318.8	13.6	6.6	1316	20.0	1.31	13.87	2.14	1.07	11.973924
A	1	100	50	10	15.8	14.8	359.0	27.2	12.3	1361	23.4	.83	2.27	.55	1.16	4.909110
~~B~~	~~1~~	~~100~~	~~50~~	~~10~~	~~15.3~~	~~14.9~~	~~357.8~~	~~27.3~~	~~10.9~~	~~1357~~	~~23.1~~	~~.36~~	~~2.37~~	~~.21~~	~~1.50~~	~~4.959254~~
B	1	100	50	30	15.1	14.6	304.7	27.3	17.4	1212	24.0	.74	1.92	.82	1.11	5.339706
*B	1	000	50	20	19.1	19.0	351.8	27.3	.0	1204	22.3	.67	2.02	.41	1.56	5.494118
~~*B~~	~~1~~	~~100~~	~~50~~	~~20~~	~~16.6~~	~~16.2~~	~~342.~~[illegible]	~~27.3~~	~~10.7~~	~~1250~~	~~21.3~~	~~.75~~	~~2.22~~	~~.28~~	~~1.68~~	~~5.535868~~
B	1	050	50	20	15.2	14.6	275.6	27.3	9.9	1193	18.3	.66	1.78	.24	1.89	5.833895
A	1	100	50	30	16.0	16.1	290.7	27.2	12.7	1204	18.6	.67	1.74	.54	1.72	6.128838
~~B~~	~~1~~	~~050~~	~~50~~	~~10~~	~~15.1~~	~~14.7~~	~~299.7~~	~~27.3~~	~~5.5~~	~~1299~~	~~18.9~~	~~.73~~	~~1.94~~	~~.15~~	~~2.09~~	~~6.161442~~
A	1	100	50	20	15.2	14.9	327.5	27.2	16.5	1297	22.5	.79	2.07	1.44	.87	6.296019
B	1	100	50	20	15.2	14.6	342.3	27.3	17.5	1286	23.7	.82	2.45	1.27	1.01	6.343149
~~B~~	~~1~~	~~050~~	~~50~~	~~30~~	~~18.6~~	~~18.1~~	~~314.7~~	~~27.3~~	~~6.3~~	~~1123~~	~~19.4~~	~~.61~~	~~1.95~~	~~.55~~	~~1.78~~	~~6.364993~~
B	1	100	50	20	18.3	17.5	364.2	27.3	7.0	1237	21.5	.73	2.23	.52	1.78	6.374175
B	1	100	50	10	18.5	18.4	432.3	27.3	2.2	1328	24.6	.85	2.64	.47	1.80	6.422812
~~A~~	~~1~~	~~100~~	~~50~~	~~10~~	~~16.2~~	~~15.5~~	~~361.4~~	~~21.8~~	~~9.2~~	~~1338~~	~~21.6~~	~~1.02~~	~~2.54~~	~~.31~~	~~2.03~~	~~6.578156~~
B	1	050	50	20	17.8	17.4	313.2	27.3	3.6	1175	19.1	.64	1.91	.17	2.27	6.651399
A	1	100	50	10	16.5	16.5	340.8	27.2	5.3	1315	20.4	.76	1.81	.16	2.34	6.772597
~~B~~	~~1~~	~~000~~	~~50~~	~~30~~	~~20.1~~	~~20.0~~	~~349.0~~	~~27.3~~	~~.0~~	~~1108~~	~~19.8~~	~~.64~~	~~2.00~~	~~.61~~	~~1.89~~	~~6.801944~~
B	1	100	50	10	16.7	16.0	362.9	27.3	6.9	1322	22.4	.79	2.35	.12	2.33	6.808859
B	1	100	50	10	17.1	17.0	368.9	27.3	4.6	1303	22.6	.79	2.38	.14	2.37	6.966463
~~A~~	~~1~~	~~100~~	~~50~~	~~20~~	~~19.2~~	~~18.9~~	~~356.4~~	~~26.5~~	~~2.3~~	~~1212~~	~~19.7~~	~~.70~~	~~2.29~~	~~.73~~	~~1.93~~	~~7.279417~~
A	1	050	50	10	15.5	14.8	298.5	27.2	5.9	1305	18.5	.71	1.89	.30	2.43	7.362590
B	1	100	50	30	16.6	15.8	319.6	27.3	15.6	1192	21.6	.70	2.07	1.62	1.17	7.485043
~~A~~	~~1~~	~~100~~	~~50~~	~~20~~	~~18.0~~	~~17.5~~	~~304.1~~	~~26.4~~	~~4.6~~	~~1216~~	~~17.6~~	~~.64~~	~~1.97~~	~~.35~~	~~2.45~~	~~7.558070~~
A	1	050	50	30	15.2	15.1	248.9	27.2	11.5	1216	16.3	.60	1.49	.59	2.31	7.652260
A	1	100	50	30	17.4	17.3	319.9	27.2	10.1	1187	19.6	.68	1.91	1.35	1.52	7.654448
~~B~~	~~1~~	~~000~~	~~50~~	~~10~~	~~18.6~~	~~18.4~~	~~406.6~~	~~27.3~~	~~.0~~	~~1285~~	~~22.6~~	~~.80~~	[illegible]	~~.31~~	~~2.49~~	~~7.710509~~
A	1	050	50	20	15.2	15.1	262.9	27.2	7.8	1246	17.1	.64	1.57	.47	2.51	7.883106
*A	1	100	50	20	16.4	16.0	286.6	26.8	8.5	1231	18.4	.65	1.84	.25	2.70	7.900933

Table P-2 (Cont.)

~~B~~	~~0~~	~~100~~	~~50~~	~~10~~	~~15.3~~	~~14.8~~	~~357.8~~	~~27.3~~	~~11.1~~	~~1357~~	~~23.1~~	~~.86~~	~~9.55~~	~~.81~~	~~1.25~~	~~7.909433~~
B	1	100	50	20	19.0	18.8	382.4	27.3	4.0	1188	22.9	.74	2.33	1.25	1.70	7.984075
B	1	050	50	20	16.6	16.3	286.6	27.3	5.5	1182	18.3	.63	1.86	.15	2.85	8.037912
~~A~~	~~1~~	~~000~~	~~50~~	~~30~~	~~20.1~~	~~19.6~~	~~335.2~~	~~27.2~~	~~.0~~	~~1141~~	~~18.9~~	~~.61~~	~~2.10~~	~~.84~~	~~2.15~~	~~8.041428~~
A	1	100	50	30	20.1	19.3	352.6	27.2	1.8	1161	19.3	.64	2.09	1.03	2.01	8.151901
B	1	100	50	30	19.7	19.7	370.9	27.3	3.3	1120	21.5	.69	2.25	1.70	1.34	8.156106
~~B~~	~~1~~	~~100~~	~~50~~	~~30~~	~~17.8~~	~~17.4~~	~~341.8~~	~~27.3~~	~~11.3~~	~~1235~~	~~22.1~~	~~.70~~	~~2.21~~	~~1.67~~	~~1.43~~	~~8.298171~~
A	1	000	50	20	19.4	19.2	355.4	26.5	.0	1206	19.8	.69	2.29	.73	2.34	8.304017
B	1	050	50	30	14.9	14.6	249.5	27.3	7.1	1139	16.4	.61	1.49	.40	2.79	8.380845
~~B~~	~~0~~	~~100~~	~~50~~	~~10~~	~~16.7~~	~~15.9~~	~~362.9~~	~~27.3~~	~~7.0~~	~~1320~~	~~22.4~~	~~.79~~	~~6.36~~	~~.58~~	~~2.13~~	~~8.463881~~
B	1	050	50	10	16.2	16.0	329.5	27.3	4.2	1278	20.1	.74	2.13	.09	3.13	8.670983
B	1	050	50	30	16.1	15.8	268.5	27.3	9.1	1151	17.1	.61	1.70	.27	3.13	8.983537
~~B~~	~~0~~	~~100~~	~~50~~	~~10~~	~~17.1~~	~~16.9~~	~~368.9~~	~~27.3~~	~~4.6~~	~~1294~~	~~22.6~~	~~.79~~	~~6.71~~	~~.59~~	~~2.27~~	~~9.087554~~
A	1	100	50	10	17.4	17.1	335.5	27.2	1.0	1306	19.3	.71	1.89	.13	3.29	9.097956
A	1	050	50	30	17.7	17.8	291.8	27.2	4.8	1160	17.6	.61	1.64	.42	3.10	9.256743
~~B~~	~~1~~	~~000~~	~~50~~	~~10~~	~~17.3~~	~~17.0~~	~~337.8~~	~~27.3~~	~~.0~~	~~1249~~	~~19.8~~	~~.71~~	~~2.10~~	~~.11~~	~~3.35~~	~~9.284469~~
B	0	050	50	10	15.1	14.8	299.7	27.3	5.5	1301	18.9	.73	8.00	.52	2.34	9.471234
B	0	050	50	20	17.8	17.5	313.2	27.3	3.6	1185	19.1	.64	7.02	.66	2.36	9.574462
~~A~~	~~0~~	~~100~~	~~50~~	~~10~~	~~16.5~~	~~16.4~~	~~340.8~~	~~27.2~~	~~5.3~~	~~1317~~	~~20.5~~	~~.76~~	~~8.04~~	~~.72~~	~~2.20~~	~~9.620803~~
B	0	000	50	20	19.1	19.1	351.8	27.3	.0	1201	22.3	.67	9.33	1.44	1.37	9.681313
B	0	100	50	20	16.6	16.2	342.1	27.3	10.9	1257	21.3	.75	9.22	1.39	1.44	9.702009
~~B~~	~~0~~	~~050~~	~~50~~	~~20~~	~~15.2~~	~~14.7~~	~~275.6~~	~~27.3~~	~~10.0~~	~~1197~~	~~18.3~~	~~.66~~	~~8.54~~	~~1.04~~	~~1.89~~	~~9.773350~~
B	0	050	50	10	16.2	16.0	329.5	27.3	4.2	1292	20.1	.74	5.55	.34	3.13	10.286621
B	1	000	50	20	24.8	17.5	315.4	27.3	.0	1193	17.7	.47	1.82	.24	3.74	10.470660
~~B~~	~~1~~	~~000~~	~~50~~	~~30~~	~~19.2~~	~~18.2~~	~~294.6~~	~~27.3~~	~~.0~~	~~1139~~	~~16.7~~	~~.57~~	~~1.88~~	~~.25~~	~~3.75~~	~~10.537697~~
A	1	100	50	30	14.6	14.9	320.3	27.2	22.0	1241	22.9	.81	2.14	3.42	.63	10.545875
B	0	050	50	20	16.6	16.2	286.6	27.3	5.5	1208	18.3	.63	6.35	.65	2.85	10.578013
~~A~~	~~0~~	~~100~~	~~50~~	~~10~~	~~15.7~~	~~15.0~~	~~359.0~~	~~27.2~~	~~12.7~~	~~1361~~	~~23.5~~	~~.84~~	~~9.93~~	~~2.12~~	~~1.06~~	~~10.741320~~
B	0	000	50	10	17.3	17.0	337.8	27.3	.0	1255	19.8	.71	5.57	.32	3.35	10.793723
B	0	100	50	10	18.5	18.5	432.3	27.3	2.3	1318	24.6	.85	9.88	1.63	1.68	11.081492
~~A~~	~~1~~	~~050~~	~~50~~	~~10~~	~~15.5~~	~~15.5~~	~~298.2~~	~~21.8~~	~~4.0~~	~~1297~~	~~17.5~~	~~.88~~	~~2.23~~	~~.22~~	~~3.97~~	~~11.117468~~
A	1	000	50	10	17.3	17.2	328.0	27.2	.0	1298	10.9	.70	1.73	.17	4.18	11.373458
A	1	000	50	10	16.5	16.4	305.8	27.2	.0	1282	18.3	.68	1.73	.13	4.30	11.575897
~~A~~	~~0~~	~~100~~	~~50~~	~~10~~	~~17.4~~	~~17.1~~	~~335.5~~	~~27.2~~	~~1.0~~	~~1306~~	~~19.3~~	~~.71~~	~~6.07~~	~~.40~~	~~3.57~~	~~11.685984~~
A	0	100	50	10	16.2	15.6	361.4	21.8	9.1	1342	21.5	1.02	11.26	1.37	2.03	11.728228
B	0	100	50	20	18.3	17.5	364.2	27.3	7.1	1234	21.5	.73	11.13	2.02	1.42	11.750359
~~A~~	~~0~~	~~100~~	~~50~~	~~20~~	~~16.4~~	~~16.0~~	~~286.6~~	~~26.8~~	~~8.6~~	~~1236~~	~~18.4~~	~~.65~~	~~7.82~~	~~1.33~~	~~2.50~~	~~11.793992~~
A	1	050	50	30	16.3	16.4	260.3	27.2	6.2	1168	16.5	.59	1.56	.33	4.24	11.863702
B	1	100	90	30	15.2	14.7	386.0	49.2	14.4	1198	25.7	.52	1.46	.45	2.10	6.776973
~~B~~	~~1~~	~~100~~	~~90~~	~~30~~	~~16.2~~	~~16.0~~	~~402.1~~	~~49.2~~	~~12.3~~	~~1189~~	~~25.9~~	~~.50~~	~~1.45~~	~~.43~~	~~2.66~~	~~8.125251~~
B	1	100	90	20	16.0	15.9	407.0	49.2	10.5	1218	25.8	.52	1.42	.25	2.84	8.127403
B	1	100	90	20	15.0	14.4	386.7	49.2	10.2	1236	25.1	.52	1.39	.64	2.94	9.319799
~~B~~	~~0~~	~~100~~	~~90~~	~~20~~	~~16.0~~	~~15.8~~	~~407.0~~	~~49.2~~	~~10.6~~	~~1217~~	~~25.8~~	~~.52~~	~~5.30~~	~~.86~~	~~2.68~~	~~10.356385~~
B	1	100	90	30	18.4	17.9	446.6	49.2	5.9	1157	26.3	.49	1.64	.31	3.76	10.638451
B	1	100	90	30	19.5	19.3	479.5	49.2	2.1	1133	26.4	.50	1.66	.33	3.80	10.793113
~~B~~	~~1~~	~~100~~	~~90~~	~~20~~	~~17.1~~	~~16.7~~	~~445.5~~	~~49.2~~	~~6.4~~	~~1220~~	~~25.9~~	~~.53~~	~~1.47~~	~~.17~~	~~4.39~~	~~11.821987~~

160 RECORDS

Table P-3

COMPUTER-SORTED SPEED, PERCENT POWER, AND TOTAL WEIGHTED EMISSION DATA – 2,400 RPM, ENGINES A AND B (PRINTED FOR SCR < 17)

E	C	RR	PP	ST	MAFR	CAFR	IAR	PO	ER	ET	MP	SFC	CO	HC	NO	SCR
~~A~~	~~1~~	~~050~~	~~10~~	~~30~~	~~15.3~~	~~15.0~~	~~241.3~~	~~9.9~~	~~9.8~~	~~1342~~	~~10.7~~	~~1.69~~	~~4.19~~	~~.73~~	~~2.60~~	~~9.512841~~
A	1	050	10	20	15.4	14.7	265.2	9.9	9.1	1394	11.1	1.74	4.11	.33	3.07	9.688702
B	1	050	10	20	15.3	14.7	300.8	10.4	9.4	1449	13.3	1.89	4.01	.63	2.85	9.840997
~~A~~	~~1~~	~~000~~	~~10~~	~~10~~	~~19.2~~	~~18.7~~	~~402.3~~	~~9.9~~	~~.0~~	~~1452~~	~~13.6~~	~~2.12~~	~~6.57~~	~~.65~~	~~2.77~~	~~10.442719~~
A	1	100	10	20	15.6	14.7	337.8	9.9	17.9	1415	15.1	2.18	5.55	1.96	1.82	10.962841
A	1	100	10	10	18.2	14.7	412.7	9.9	11.3	1554	16.7	2.29	6.39	.34	3.34	11.058680
~~B~~	~~1~~	~~050~~	~~10~~	~~20~~	~~16.2~~	~~16.0~~	~~310.4~~	~~11.0~~	~~6.6~~	~~1438~~	~~13.5~~	~~1.74~~	~~4.06~~	~~.45~~	~~3.55~~	~~11.166679~~
B	1	100	10	20	16.3	16.0	381.9	11.0	13.4	1460	17.5	2.12	5.32	1.67	2.38	11.587877
B	1	050	10	20	18.4	17.8	366.1	10.2	5.0	1414	15.1	1.95	5.80	1.23	2.86	11.855882
~~B~~	~~1~~	~~100~~	~~10~~	~~10~~	~~15.9~~	~~14.7~~	~~413.0~~	~~10.4~~	~~9.0~~	~~1570~~	~~17.5~~	~~2.48~~	~~5.68~~	~~.54~~	~~3.61~~	~~12.012661~~
A	1	050	10	20	16.6	16.7	321.4	9.9	6.4	1442	13.0	1.95	5.88	.67	3.47	12.038558
A	1	050	10	30	16.8	16.5	286.7	9.9	8.0	1364	11.9	1.73	4.71	1.33	3.10	12.379197
~~B~~	~~1~~	~~050~~	~~10~~	~~30~~	~~15.4~~	~~14.8~~	~~263.1~~	~~11.5~~	~~7.8~~	~~1357~~	~~11.5~~	~~1.48~~	~~3.92~~	~~.54~~	~~4.01~~	~~12.495014~~
B	1	100	10	10	16.5	16.0	424.6	10.7	8.4	1555	17.7	2.41	5.74	.40	3.95	12.538845
A	1	050	10	10	15.4	14.7	319.7	9.9	5.4	1500	12.7	2.09	4.95	.16	4.31	12.621126
~~A~~	~~1~~	~~100~~	~~10~~	~~10~~	~~19.1~~	~~18.7~~	~~447.0~~	~~9.9~~	~~4.0~~	~~1453~~	~~17.0~~	~~2.36~~	~~7.30~~	~~1.86~~	~~2.40~~	~~12.683644~~
A	0	050	10	10	15.4	14.8	319.7	9.9	5.5	1495	12.7	2.09	9.00	.18	3.94	12.936083
B	1	050	10	30	16.2	16.1	273.0	10.4	7.5	1360	12.1	1.61	3.65	1.02	3.80	13.061334
~~A~~	~~1~~	~~100~~	~~10~~	~~10~~	~~17.2~~	~~16.9~~	~~420.0~~	~~9.9~~	~~5.4~~	~~1523~~	~~16.1~~	~~2.46~~	~~7.29~~	~~.58~~	~~3.88~~	~~13.258752~~
B	1	100	10	10	18.7	17.9	431.1	10.3	.6	1500	16.5	2.23	6.56	.44	4.12	13.302582
B	1	000	10	20	18.3	17.9	339.3	10.9	.0	1389	13.5	1.69	4.74	.47	4.37	13.465459
~~B~~	~~1~~	~~050~~	~~10~~	~~10~~	~~15.3~~	~~14.8~~	~~330.0~~	~~10.4~~	~~4.1~~	~~1520~~	~~13.8~~	~~2.06~~	~~4.10~~	~~.36~~	~~4.57~~	~~13.508431~~
B	0	050	10	10	15.3	14.8	330.0	10.4	4.1	1517	13.8	2.06	4.10	.36	4.57	13.508931
A	0	050	10	20	15.4	14.8	265.2	9.9	9.1	1402	11.1	1.74	15.55	.83	3.07	14.272920
~~A~~	~~0~~	~~100~~	~~10~~	~~10~~	~~18.2~~	~~14.8~~	~~412.7~~	~~9.9~~	~~11.3~~	~~1554~~	~~16.7~~	~~2.29~~	~~13.35~~	~~.86~~	~~3.34~~	~~14.374032~~
B	1	050	10	30	17.6	17.5	328.3	10.7	8.1	1334	14.4	1.74	4.70	2.46	2.92	14.682353
A	1	000	10	20	16.8	16.6	284.5	9.9	.0	1391	11.1	1.71	4.67	.56	4.83	14.814383
~~B~~	~~1~~	~~050~~	~~10~~	~~10~~	~~16.5~~	~~16.0~~	~~366.8~~	~~10.3~~	~~3.6~~	~~1518~~	~~14.9~~	~~2.15~~	~~5.12~~	~~.20~~	~~5.16~~	~~14.893687~~
A	1	000	10	30	16.4	16.5	239.2	9.9	.0	1308	9.8	1.47	3.93	.72	4.80	14.911980
A	1	050	10	10	17.1	16.7	377.5	9.9	2.7	1515	14.0	2.23	6.91	.44	4.80	15.105524
~~A~~	~~1~~	~~000~~	~~10~~	~~20~~	~~20.9~~	~~19.6~~	~~388.9~~	~~9.4~~	~~.0~~	~~1343~~	~~14.0~~	~~1.88~~	~~6.33~~	~~4.12~~	~~1.34~~	~~15.260545~~
A	0	050	10	10	17.0	16.7	377.5	9.9	2.7	1510	14.0	2.24	9.92	.44	4.51	15.265818
A	0	000	10	10	19.3	18.7	404.5	9.9	.0	1472	13.5	2.12	15.66	1.87	2.48	15.366858
~~B~~	~~1~~	~~000~~	~~10~~	~~30~~	~~17.8~~	~~17.9~~	~~288.1~~	~~10.6~~	~~.0~~	~~1319~~	~~11.9~~	~~1.53~~	~~3.78~~	~~.37~~	~~5.39~~	~~15.489204~~
B	1	000	10	20	14.7	14.6	245.2	10.4	.0	1377	10.4	1.60	3.60	.78	5.02	15.511263
B	1	000	10	10	18.8	17.9	426.7	10.3	.0	1501	16.2	2.17	14.15	.26	4.34	15.645911
~~A~~	~~1~~	~~000~~	~~10~~	~~10~~	~~14.9~~	~~14.7~~	~~265.3~~	~~9.9~~	~~.0~~	~~1958~~	~~10.6~~	~~1.80~~	~~4.11~~	~~.18~~	~~5.63~~	~~15.722848~~
A	0	050	10	20	16.6	16.6	321.4	9.9	6.4	1440	12.9	1.96	13.12	1.49	3.47	16.167970
B	0	100	10	10	16.5	16.0	424.6	10.7	8.4	1556	17.7	2.41	13.88	1.33	3.65	16.451255
~~B~~	~~1~~	~~000~~	~~10~~	~~10~~	~~15.0~~	~~14.7~~	~~299.7~~	~~10.4~~	~~.0~~	~~1507~~	~~12.3~~	~~1.81~~	~~4.13~~	~~.53~~	~~3.58~~	~~16.457389~~
B	0	050	10	20	16.2	16.0	310.4	11.0	6.7	1425	13.5	1.74	13.61	1.81	3.23	16.492575
A	1	000	10	20	14.7	14.7	224.4	9.9	.0	1341	9.2	1.55	3.58	.34	5.89	16.607209
~~B~~	~~0~~	~~050~~	~~10~~	~~10~~	~~16.5~~	~~16.0~~	~~366.8~~	~~10.3~~	~~4.1~~	~~1518~~	~~14.9~~	~~2.15~~	~~11.07~~	~~.61~~	~~4.75~~	~~16.618687~~
A	1	000	10	10	16.4	16.6	341.8	9.9	.0	1483	13.1	2.10	6.26	.40	5.54	16.666786
A	1	100	10	30	16.5	16.0	338.2	9.9	16.4	1351	15.3	2.07	5.89	4.33	1.83	16.868329
~~A~~	~~1~~	~~100~~	~~25~~	~~30~~	~~16.7~~	~~16.1~~	~~393.9~~	~~24.8~~	~~14.9~~	~~1378~~	~~16.8~~	~~.95~~	~~2.51~~	~~.20~~	~~1.46~~	~~4.876944~~
A	1	100	25	20	16.0	14.8	421.0	25.6	12.8	1470	17.6	1.03	3.05	.19	1.63	5.435473
A	1	100	25	20	16.0	16.2	437.9	24.8	11.3	1468	17.9	1.10	2.79	.14	1.82	5.712052
~~A~~	~~1~~	~~000~~	~~25~~	~~30~~	~~20.4~~	~~20.9~~	~~473.2~~	~~25.4~~	~~.0~~	~~1321~~	~~17.9~~	~~.91~~	~~2.83~~	~~.68~~	~~1.34~~	~~5.840890~~
A	1	100	25	30	15.9	14.7	384.5	25.8	15.6	1384	16.4	.94	2.83	.38	1.70	6.009182
A	1	050	25	30	18.8	18.3	379.6	25.2	5.2	1339	14.7	.80	2.58	.30	1.83	6.065531
~~A~~	~~1~~	~~100~~	~~25~~	~~10~~	~~15.7~~	~~14.7~~	~~484.4~~	~~25.4~~	~~10.6~~	~~1554~~	~~20.6~~	~~1.22~~	~~3.54~~	~~.11~~	~~2.04~~	~~6.409469~~
A	1	100	25	20	18.7	17.9	459.2	24.8	4.8	1407	17.3	.99	3.34	.30	1.97	6.639060
A	1	100	25	10	17.0	16.4	503.1	26.1	8.1	1535	20.0	1.13	3.67	.04	2.35	7.051973
~~B~~	~~1~~	~~100~~	~~25~~	~~20~~	~~15.6~~	~~14.7~~	~~408.2~~	~~25.2~~	~~11.0~~	~~1449~~	~~17.7~~	~~1.04~~	~~2.71~~	~~.22~~	~~2.35~~	~~7.298644~~
A	1	050	25	10	15.2	14.7	408.3	25.4	6.2	1504	16.3	1.06	3.36	.15	2.58	7.804089
A	1	050	25	20	21.7	20.0	578.5	24.8	3.1	1406	20.9	1.07	3.54	1.33	1.41	7.810079

Table P-3 (Cont.)

~~A~~	~~0~~	~~050~~	~~25~~	~~30~~	~~18.6~~	~~18.2~~	~~379.6~~	~~26.4~~	~~5.3~~	~~1334~~	~~14.7~~	~~.77~~	~~9.05~~	~~.59~~	~~1.53~~	~~7.925789~~
A	1	050	25	30	16.1	16.1	322.7	24.8	7.1	1336	13.4	.81	2.00	.08	2.88	7.983357
A	1	050	25	20	15.4	14.8	339.5	25.4	6.8	1403	13.4	.87	2.48	.06	2.86	8.025753
~~A~~	~~1~~	~~100~~	~~25~~	~~10~~	~~19.5~~	~~18.3~~	~~552.9~~	~~25.2~~	~~3.5~~	~~1473~~	~~20.4~~	~~1.12~~	~~3.34~~	~~.52~~	~~2.34~~	~~8.100646~~
A	0	100	25	10	17.0	16.4	503.1	26.1	8.1	1535	20.0	1.13	6.18	.18	2.35	8.131671
A	0	100	25	20	16.0	14.8	421.0	25.6	13.0	1454	17.6	1.03	11.12	.64	1.38	8.281564
~~B~~	~~1~~	~~100~~	~~25~~	~~30~~	~~18.4~~	~~17.9~~	~~497.9~~	~~24.4~~	~~6.6~~	~~1328~~	~~17.7~~	~~.96~~	~~3.01~~	~~.30~~	~~2.07~~	~~8.292001~~
A	1	050	25	20	16.0	16.2	356.1	25.4	4.9	1407	14.1	.87	2.15	.07	3.00	8.303085
A	0	100	25	20	16.0	16.2	437.9	24.8	11.4	1457	17.9	1.10	8.37	.65	1.75	8.422131
~~B~~	~~1~~	~~100~~	~~25~~	~~10~~	~~16.5~~	~~14.7~~	~~515.2~~	~~24.4~~	~~9.9~~	~~1551~~	~~21.3~~	~~1.28~~	~~3.63~~	~~.16~~	~~2.82~~	~~8.507891~~
A	1	100	25	20	20.3	18.9	547.8	24.8	6.0	1411	20.9	1.09	3.36	1.46	1.59	8.524211
B	1	100	25	20	16.6	15.6	436.4	24.7	17.0	1371	20.0	1.06	3.21	1.79	1.35	8.684971
~~A~~	~~0~~	~~050~~	~~25~~	~~10~~	~~17.2~~	~~16.4~~	~~451.3~~	~~25.3~~	~~4.8~~	~~1547~~	~~17.8~~	~~1.04~~	~~5.56~~	~~.02~~	~~2.86~~	~~8.834075~~
A	1	050	25	10	17.2	16.4	451.3	25.3	4.8	1504	17.8	1.04	3.40	.01	3.13	8.849390
A	1	000	25	10	19.8	18.5	523.9	25.2	.0	1463	18.0	1.05	3.17	.26	3.00	9.066499
~~A~~	~~1~~	~~000~~	~~25~~	~~20~~	~~18.5~~	~~18.0~~	~~417.8~~	~~25.4~~	~~.0~~	~~1379~~	~~15.2~~	~~.89~~	~~2.13~~	~~.03~~	~~3.38~~	~~9.149641~~
A	0	050	25	20	16.0	16.0	354.7	25.4	4.9	1408	13.9	.87	5.47	.16	2.89	9.224067
A	1	100	25	30	19.0	18.4	470.0	25.3	11.1	1314	19.3	.98	3.35	2.38	.99	9.265172
~~A~~	~~0~~	~~100~~	~~25~~	~~20~~	~~18.7~~	~~17.9~~	~~459.2~~	~~24.8~~	~~4.8~~	~~1403~~	~~17.3~~	~~.90~~	~~8.81~~	~~.83~~	~~1.97~~	~~9.540567~~
A	0	100	25	30	16.7	16.2	393.9	25.1	14.4	1377	17.1	.94	12.99	1.81	.54	9.585222
A	0	000	25	10	19.8	18.4	523.9	25.2	.0	1462	18.0	1.05	6.82	.52	2.57	9.690175
~~B~~	~~1~~	~~100~~	~~25~~	~~30~~	~~15.6~~	~~14.5~~	~~416.9~~	~~24.9~~	~~19.2~~	~~1367~~	~~20.1~~	~~1.07~~	~~2.72~~	~~1.69~~	~~1.92~~	~~9.721951~~
B	1	050	25	20	18.9	17.5	456.6	24.9	2.3	1389	17.6	.97	2.97	.23	3.42	9.984505
B	1	050	25	20	15.2	14.7	349.8	24.6	6.3	1409	14.7	.93	2.37	.16	3.57	10.012303
~~A~~	~~1~~	~~050~~	~~25~~	~~30~~	~~15.4~~	~~14.7~~	~~307.5~~	~~25.4~~	~~6.2~~	~~1335~~	~~13.6~~	~~.78~~	~~1.74~~	~~.11~~	~~3.70~~	~~10.030057~~
A	0	050	25	30	16.7	16.1	327.1	24.8	7.1	1299	13.4	.79	7.17	.36	2.82	10.036872
B	1	050	25	30	15.8	14.6	339.2	25.2	9.9	1348	14.9	.85	1.94	.42	3.39	10.069978
~~A~~	~~1~~	~~000~~	~~25~~	~~20~~	~~21.2~~	~~20.3~~	~~565.3~~	~~25.6~~	~~.0~~	~~1400~~	~~19.9~~	~~1.04~~	~~3.35~~	~~2.11~~	~~1.58~~	~~10.081636~~
A	1	050	25	30	20.8	20.8	508.1	24.8	2.7	1276	18.7	.98	3.10	2.51	1.24	10.133716
A	0	000	25	20	18.5	17.9	417.8	25.4	.0	1376	15.2	.89	6.32	.18	3.38	10.747848
~~B~~	~~1~~	~~100~~	~~25~~	~~20~~	~~18.0~~	~~17.3~~	~~535.5~~	~~24.9~~	~~9.7~~	~~1402~~	~~22.8~~	~~1.20~~	~~3.69~~	~~1.78~~	~~2.13~~	~~10.751758~~
B	1	100	25	30	16.4	16.1	351.8	24.5	8.1	1329	15.4	.88	2.07	.22	3.85	10.770409
B	1	100	25	10	19.6	17.8	612.6	24.9	2.9	1516	23.1	1.26	3.99	.31	3.55	10.804627
~~A~~	~~0~~	~~100~~	~~25~~	~~10~~	~~15.7~~	~~14.8~~	~~484.4~~	~~25.4~~	~~10.6~~	~~1553~~	~~20.6~~	~~1.22~~	~~9.12~~	~~.39~~	~~2.91~~	~~10.998572~~
B	1	050	25	10	15.5	14.7	417.6	24.6	4.9	1500	17.2	1.10	2.91	.15	3.95	11.096736
A	1	000	25	30	18.3	18.4	351.5	25.5	.0	1308	13.2	.75	2.10	.11	4.09	11.110940
~~A~~	~~1~~	~~000~~	~~25~~	~~10~~	~~14.4~~	~~14.7~~	~~341.8~~	~~24.7~~	~~.0~~	~~1461~~	~~13.2~~	~~.96~~	~~2.67~~	~~.17~~	~~4.01~~	~~11.195516~~
B	1	000	25	20	18.7	17.9	442.5	24.9	.0	1374	17.1	.95	2.88	.37	3.78	11.199498
B	1	050	25	30	18.1	17.9	397.6	24.6	3.6	1312	14.8	.89	2.76	.16	4.05	11.327009
~~A~~	~~0~~	~~100~~	~~25~~	~~10~~	~~18.0~~	~~17.0~~	~~530.8~~	~~25.2~~	~~5.1~~	~~1528~~	~~19.8~~	~~1.17~~	~~5.47~~	~~.20~~	~~3.77~~	~~11.521628~~
B	0	100	25	20	15.6	14.8	409.8	25.2	11.2	1447	17.7	1.04	13.76	1.01	2.05	11.635473
B	1	000	25	10	19.5	17.9	569.5	24.9	.0	1492	21.1	1.17	3.49	.16	4.09	11.641714
~~A~~	~~1~~	~~100~~	~~25~~	~~10~~	~~18.0~~	~~16.9~~	~~530.8~~	~~26.2~~	~~5.1~~	~~1532~~	~~9.8~~	~~1.17~~	~~3.42~~	~~.14~~	~~4.10~~	~~11.797346~~
A	0	050	25	20	15.4	14.8	338.3	25.4	6.9	1400	13.4	.87	12.62	.31	2.95	11.842862
A	0	100	25	10	19.5	18.3	552.9	25.2	3.6	1474	20.4	1.12	9.94	1.51	2.17	12.031456
~~A~~	~~1~~	~~000~~	~~25~~	~~10~~	~~17.9~~	~~17.2~~	~~439.7~~	~~25.2~~	~~.0~~	~~1457~~	~~16.0~~	~~.98~~	~~2.75~~	~~.13~~	~~4.39~~	~~12.100897~~
A	1	000	25	10	16.8	16.4	414.6	25.6	.0	1472	16.3	.97	3.09	.01	4.52	12.233214
B	0	050	25	20	18.9	17.6	458.9	24.9	2.3	1389	17.5	.98	9.81	.68	3.08	12.243831
~~B~~	~~0~~	~~100~~	~~25~~	~~10~~	~~16.4~~	~~14.8~~	~~613.3~~	~~24.4~~	~~9.9~~	~~1552~~	~~21.3~~	~~1.28~~	~~13.69~~	~~.67~~	~~2.65~~	~~12.285617~~
A	0	100	25	30	15.9	14.8	384.9	26.1	15.8	1385	16.4	.93	13.97	1.86	1.57	12.570409
B	0	000	25	10	19.3	17.8	567.3	24.9	.0	1495	21.1	1.18	7.49	.42	3.81	12.752331
~~A~~	~~0~~	~~000~~	~~25~~	~~10~~	~~16.8~~	~~16.3~~	~~414.6~~	~~25.6~~	~~.0~~	~~1474~~	~~16.3~~	~~.97~~	~~5.05~~	~~.04~~	~~4.52~~	~~12.882855~~
B	1	050	25	20	16.4	16.0	339.8	24.4	5.8	1324	14.5	.85	2.01	.39	4.58	12.992396
A	0	100	25	20	20.2	19.1	545.7	24.8	6.3	1411	20.9	1.09	18.55	1.90	1.17	13.015029
~~B~~	~~1~~	~~000~~	~~25~~	~~30~~	~~22.1~~	~~21.1~~	~~540.7~~	~~25.2~~	~~.0~~	~~1276~~	~~20.1~~	~~.97~~	~~3.65~~	~~3.32~~	~~1.54~~	~~13.021090~~
A	0	000	25	10	17.9	17.1	439.7	25.2	.0	1455	16.0	.98	4.94	.16	4.52	13.143185
A	0	000	25	30	18.3	18.3	351.5	25.5	.0	1306	13.2	.75	7.46	.39	4.09	13.370337
~~A~~	~~1~~	~~000~~	~~25~~	~~20~~	~~16.5~~	~~16.1~~	~~340.7~~	~~24.8~~	~~.0~~	~~1384~~	~~13.1~~	~~.83~~	~~2.11~~	~~.09~~	~~5.05~~	~~13.415100~~
A	1	100	25	30	20.8	20.6	521.2	24.6	4.8	1270	19.6	1.02	3.61	4.20	1.12	14.105667
B	0	050	25	30	15.9	14.8	340.1	25.2	10.2	1350	14.8	.85	9.16	1.27	3.40	14.291679

Lockheed

Table P-3 (Cont.)

~~A~~	~~0~~	~~100~~	~~25~~	~~30~~	~~18.4~~	~~18.0~~	~~427.9~~	~~24.4~~	~~6.7~~	~~1326~~	~~17.6~~	~~.96~~	~~15.76~~	~~1.93~~	~~2.00~~	~~14.342611~~
A	1	000	25	20	14.8	14.8	310.2	25.4	.0	1387	12.0	.82	2.27	.11	5.41	14.460940
A	0	000	25	20	16.2	16.0	336.3	24.8	.0	1380	12.9	.83	5.61	.22	4.97	14.611585
~~B~~	~~0~~	~~950~~	~~25~~	~~20~~	~~15.2~~	~~14.8~~	~~349.8~~	~~24.6~~	~~6.4~~	~~1407~~	~~14.7~~	~~.93~~	~~12.00~~	~~.99~~	~~3.58~~	~~14.796485~~
B	0	100	25	30	16.4	16.0	351.8	24.6	8.2	1331	15.4	.87	9.44	1.12	3.82	15.058178
B	1	000	25	20	21.1	20.5	604.3	24.4	.0	1364	22.3	1.18	4.22	3.66	1.97	15.093006
~~B~~	~~0~~	~~050~~	~~25~~	~~30~~	~~18.2~~	~~17.9~~	~~397.6~~	~~24.6~~	~~3.7~~	~~1306~~	~~15.9~~	~~.89~~	~~11.72~~	~~.85~~	~~3.93~~	~~15.345230~~
B	1	000	25	30	18.1	17.9	375.6	24.4	.0	1290	14.9	.85	2.64	.15	5.74	15.492324
B	1	000	25	10	14.7	14.7	368.2	24.6	.0	1475	15.0	1.01	2.57	.22	5.70	15.542468
~~A~~	~~0~~	~~050~~	~~25~~	~~30~~	~~15.4~~	~~14.8~~	~~306.3~~	~~25.4~~	~~6.3~~	~~1338~~	~~13.6~~	~~.78~~	~~14.69~~	~~.50~~	~~4.14~~	~~15.8901[illegible]~~
A	0	050	25	10	15.2	14.7	408.3	25.4	6.5	1503	16.3	1.06	32.86	.37	2.27	16.242145
B	0	000	25	20	18.5	17.8	440.2	24.9	.0	1377	17.2	.96	9.41	2.02	3.49	16.419476
~~B~~	~~1~~	~~050~~	~~25~~	~~10~~	~~19.4~~	~~17.8~~	~~612.6~~	~~24.9~~	~~2.9~~	~~1512~~	~~23.4~~	~~1.26~~	~~10.82~~	~~1.80~~	~~3.55~~	~~16.447597~~
B	0	100	25	10	19.5	17.8	612.7	24.9	2.9	1512	23.4	1.26	10.82	1.80	3.55	16.447597
B	0	050	25	20	16.4	16.0	339.8	24.4	5.8	1328	14.5	.85	8.50	1.17	4.65	16.978659
~~A~~	~~1~~	~~050~~	~~50~~	~~30~~	~~20.9~~	~~20.3~~	~~569.7~~	~~48.2~~	~~1.6~~	~~1321~~	~~21.1~~	~~.57~~	~~1.79~~	~~.32~~	~~1.96~~	~~6.246958~~
A	1	100	50	20	19.2	18.3	607.5	48.6	6.6	1418	22.5	.65	2.08	.08	2.23	6.381807
A	1	100	50	30	16.2	14.8	464.0	49.2	12.2	1364	19.3	.58	1.71	.13	2.37	6.745014
~~A~~	~~1~~	~~100~~	~~50~~	~~20~~	~~15.6~~	~~14.9~~	~~485.4~~	~~49.7~~	~~8.9~~	~~1430~~	~~19.6~~	~~.63~~	~~1.41~~	~~.08~~	~~2.46~~	~~6.759628~~
A	1	100	50	30	19.6	18.3	567.3	50.8	7.4	1340	21.9	.57	1.81	.35	2.21	6.911011
A	1	100	50	20	17.2	16.1	562.0	49.5	12.7	1373	22.5	.66	1.96	.25	2.34	7.036227
~~A~~	~~1~~	~~100~~	~~50~~	~~30~~	~~16.6~~	~~15.9~~	~~493.6~~	~~50.1~~	~~15.2~~	~~1980~~	~~20.9~~	~~.59~~	~~1.79~~	~~.68~~	~~1.96~~	~~7.085007~~
A	1	100	50	30	20.8	20.2	614.2	48.2	4.1	1311	23.2	.61	2.02	1.16	1.54	7.273386
A	0	100	50	20	19.2	18.2	607.5	48.6	6.6	1420	22.5	.65	5.55	.31	1.99	7.363451
~~A~~	~~1~~	~~000~~	~~50~~	~~20~~	~~20.6~~	~~18.9~~	~~588.4~~	~~47.3~~	~~.0~~	~~1388~~	~~21.0~~	~~.60~~	~~1.78~~	~~.11~~	~~2.64~~	~~7.391822~~
A	1	000	50	30	20.7	20.2	569.7	49.1	.0	1313	20.4	.56	1.76	.32	2.45	7.423135
A	1	100	50	20	19.9	18.9	614.5	47.8	1.2	1401	21.8	.64	1.84	.09	2.73	7.585689
~~A~~	~~1~~	~~050~~	~~50~~	~~20~~	~~18.9~~	~~18.2~~	~~553.0~~	~~50.9~~	~~2.5~~	~~1395~~	~~20.3~~	~~.57~~	~~1.81~~	~~.03~~	~~2.89~~	~~7.830524~~
B	1	100	50	30	15.7	14.7	516.6	51.1	13.6	1374	22.5	.64	1.74	.33	2.81	8.341643
A	0	900	50	20	20.6	18.8	590.6	47.3	.0	1389	21.0	.60	5.30	.26	2.46	8.342970
~~A~~	~~0~~	~~050~~	~~50~~	~~20~~	~~18.9~~	~~18.2~~	~~553.0~~	~~50.9~~	~~2.5~~	~~1393~~	~~20.3~~	~~.57~~	~~4.37~~	~~.10~~	~~2.73~~	~~8.354197~~
A	0	100	50	20	15.6	14.9	485.4	49.7	9.0	1426	19.6	.63	6.71	.22	2.38	8.460115
A	0	100	50	20	19.9	18.8	614.5	47.8	1.2	1401	21.8	.64	5.46	.22	2.53	8.467468
~~A~~	~~1~~	~~000~~	~~50~~	~~20~~	~~18.8~~	~~18.4~~	~~537.6~~	~~49.1~~	~~.0~~	~~1378~~	~~20.0~~	~~.58~~	~~1.87~~	~~.06~~	~~3.45~~	~~9.321341~~
A	1	100	50	10	15.9	14.8	529.0	48.8	4.6	1517	20.2	.58	1.76	.05	3.52	9.439598
A	1	050	50	30	18.3	18.2	504.5	51.3	3.6	1326	18.7	.54	1.50	.09	3.59	9.635689
~~A~~	~~0~~	~~100~~	~~50~~	~~30~~	~~16.2~~	~~14.9~~	~~464.0~~	~~49.2~~	~~12.4~~	~~1364~~	~~19.3~~	~~.58~~	~~9.99~~	~~.59~~	~~2.16~~	~~9.777260~~
B	1	100	50	20	16.0	14.7	558.1	48.6	11.7	1437	23.8	.72	2.08	.21	3.50	9.873960
A	0	050	50	30	20.9	20.3	569.7	48.2	1.6	1303	21.1	.57	8.91	1.24	1.70	9.894978
~~A~~	~~0~~	~~000~~	~~50~~	~~30~~	~~20.7~~	~~20.1~~	~~569.7~~	~~49.1~~	~~.0~~	~~1313~~	~~20.4~~	~~.56~~	~~7.79~~	~~.79~~	~~2.28~~	~~9.918006~~
A	0	000	50	20	18.8	18.2	537.6	49.1	.0	1378	20.0	.58	4.45	.14	3.32	9.950287
A	0	100	50	20	17.1	16.1	562.0	49.5	12.9	1376	22.5	.66	8.09	.92	2.26	10.273314
~~A~~	~~1~~	~~050~~	~~50~~	~~20~~	~~15.1~~	~~14.9~~	~~430.0~~	~~48.2~~	~~4.6~~	~~1395~~	~~17.1~~	~~.59~~	~~1.37~~	~~.12~~	~~3.95~~	~~10.570624~~
A	1	000	50	10	19.2	17.7	644.7	50.1	.0	1453	22.8	.67	2.09	.14	3.92	10.756169
A	0	000	50	10	19.2	17.7	644.7	50.1	.0	1450	22.8	.67	3.58	.16	3.92	11.243185
~~B~~	~~1~~	~~100~~	~~50~~	~~30~~	~~17.4~~	~~16.1~~	~~566.5~~	~~50.0~~	~~10.9~~	~~1355~~	~~23.2~~	~~.67~~	~~1.84~~	~~.26~~	~~4.03~~	~~11.250323~~
B	1	100	50	20	17.5	16.1	587.1	50.0	7.3	1415	23.9	.67	1.80	.16	4.17	11.344656
A	1	100	50	10	18.7	17.6	653.6	50.1	1.2	1451	24.1	.70	2.12	.12	4.22	11.466212
~~A~~	~~1~~	~~950~~	~~50~~	~~30~~	~~16.9~~	~~16.2~~	~~429.7~~	~~50.1~~	~~9.0~~	~~1280~~	~~17.2~~	~~.51~~	~~1.48~~	~~.19~~	~~4.26~~	~~11.548799~~
A	0	050	50	30	18.3	18.2	504.5	51.3	3.6	1329	18.7	.54	6.05	.34	3.59	11.583680
B	1	100	50	30	18.6	17.9	615.1	50.0	7.0	1327	24.3	.66	1.99	.45	4.02	11.732855
~~A~~	~~0~~	~~100~~	~~50~~	~~10~~	~~18.7~~	~~17.6~~	~~653.6~~	~~50.1~~	~~1.2~~	~~1452~~	~~24.1~~	~~.70~~	~~3.63~~	~~.13~~	~~4.22~~	~~11.934720~~
A	0	100	50	10	15.9	14.8	530.9	48.8	4.6	1517	20.4	.68	11.52	.12	3.45	12.305918
A	0	100	50	30	19.6	18.4	567.3	50.8	7.6	1338	21.9	.57	10.54	1.92	1.87	12.457927
~~A~~	~~1~~	~~050~~	~~50~~	~~20~~	~~17.1~~	~~16.1~~	~~484.6~~	~~49.5~~	~~6.9~~	~~1330~~	~~18.8~~	~~.57~~	~~1.69~~	~~.11~~	~~4.87~~	~~12.940352~~
B	1	100	50	20	19.6	18.0	677.5	50.0	1.6	1392	24.4	.69	2.19	.20	4.78	13.081923
B	0	100	50	20	17.5	16.0	587.1	50.0	7.3	1414	23.9	.67	6.50	.57	4.08	13.502009
~~A~~	~~0~~	~~050~~	~~50~~	~~30~~	~~16.9~~	~~16.2~~	~~429.7~~	~~50.1~~	~~9.0~~	~~1279~~	~~17.2~~	~~.51~~	~~3.51~~	~~.55~~	~~4.33~~	~~13.787052~~
A	1	900	50	10	15.0	14.8	477.1	48.2	.0	1487	18.2	.66	1.70	.08	5.28	13.895122
B	0	100	50	20	16.1	14.8	560.2	48.6	11.7	1435	23.8	.72	12.21	.82	3.34	13.941176

Table P-3 (Cont.)

B	1	100	50	30	20.9	19.3	705.8	50.0	3.6	1310	25.8	.67	2.28	1.96	3.52	14.251076
A	1	050	50	30	15.2	14.8	396.5	48.3	5.5	1328	15.9	.54	1.49	.17	5.39	14.327869
~~B~~	~~0~~	~~100~~	~~50~~	~~30~~	~~15.7~~	~~14.7~~	~~516.6~~	~~51.1~~	~~13.9~~	~~1373~~	~~22.5~~	~~.64~~	~~16.43~~	~~1.35~~	~~2.54~~	~~14.475036~~
A	0	100	50	30	16.5	15.9	493.6	50.1	15.6	1304	20.9	.59	10.78	2.72	1.88	14.504735
A	0	050	50	20	17.1	16.1	484.6	49.5	7.0	1336	18.8	.57	5.20	.29	4.94	14.586729
~~A~~	~~1~~	~~100~~	~~50~~	~~10~~	~~17.0~~	~~16.0~~	~~553.5~~	~~49.5~~	~~1.2~~	~~1485~~	~~19.1~~	~~.66~~	~~5.73~~	~~.08~~	~~5.22~~	~~14.930416~~
B	1	100	50	10	15.8	14.7	595.5	49.5	4.1	1506	23.4	.76	2.07	.13	5.69	15.150897
B	0	100	50	30	17.1	16.1	566.5	50.0	10.9	1356	23.3	.66	9.49	1.30	3.68	15.161908
~~B~~	~~0~~	~~100~~	~~50~~	~~20~~	~~19.8~~	~~18.0~~	~~679.8~~	~~50.0~~	~~1.6~~	~~1395~~	~~24.5~~	~~.69~~	~~7.23~~	~~.59~~	~~4.65~~	~~15.190495~~
B	0	100	50	30	18.8	17.9	617.6	50.0	7.1	1323	24.0	.66	10.97	1.41	3.57	15.590495
A	1	000	50	10	17.0	16.1	551.3	49.3	.0	1483	19.9	.66	1.51	.04	6.16	15.941679
~~A~~	~~0~~	~~050~~	~~50~~	~~20~~	~~15.1~~	~~14.8~~	~~430.0~~	~~48.2~~	~~4.7~~	~~1400~~	~~17.1~~	~~.59~~	~~17.27~~	~~.59~~	~~3.78~~	~~15.968436~~
A	1	000	50	30	19.8	18.3	499.9	49.1	.0	1305	17.2	.51	1.55	.07	6.18	16.076614
B	1	050	50	20	15.5	14.7	507.2	50.5	5.4	1407	20.5	.65	1.82	.24	6.06	16.270660
~~A~~	~~0~~	~~000~~	~~50~~	~~10~~	~~17.0~~	~~16.1~~	~~551.3~~	~~49.3~~	~~.0~~	~~1483~~	~~19.9~~	~~.66~~	~~3.12~~	~~.05~~	~~6.16~~	~~16.439598~~
B	1	000	50	20	19.2	18.0	644.2	50.0	.0	1380	23.3	.67	1.85	.18	6.21	16.508142
A		00	50	10	17.0	16.0	553.5	49.5	1.2	1485	19.1	.66	8.81	.15	5.44	16.557030
~~A~~		~~050~~	~~50~~	~~30~~	~~18.8~~	~~18.0~~	~~584.2~~	~~50.0~~	~~3.7~~	~~1313~~	~~22.5~~	~~.62~~	~~1.78~~	~~.23~~	~~6.21~~	~~16.609505~~
A	1	000	50	20	15.2	14.9	409.5	48.6	.0	1382	15.8	.56	1.29	.15	6.49	16.970265
B	1	000	50	30	20.6	19.2	649.8	50.0	.0	1307	23.6	.63	1.98	1.78	4.82	16.973816
~~A~~	~~1~~	~~100~~	~~KL~~	~~30~~	~~16.6~~	~~16.1~~	~~580.7~~	~~62.4~~	~~12.4~~	~~1346~~	~~23.7~~	~~.56~~	~~1.60~~	~~.27~~	~~3.03~~	~~8.704125~~
B	1	100	KL	30	15.4	14.7	552.7	69.1	12.2	1342	23.7	.52	1.93	.50	3.09	9.512159
A	0	100	KL	30	16.8	16.1	585.3	62.4	12.6	1345	23.7	.56	7.86	.86	2.87	11.584326
~~B~~	~~1~~	~~100~~	~~KL~~	~~30~~	~~17.3~~	~~16.4~~	~~636.8~~	~~73.0~~	~~9.8~~	~~1317~~	~~25.7~~	~~.50~~	~~1.79~~	~~.20~~	~~4.40~~	~~12.014275~~
B	1	100	KL	20	16.8	16.5	629.1	71.0	5.6	1363	25.2	.53	1.61	.10	5.34	14.067432
A	1	100	KL	20	16.7	16.3	614.7	62.4	6.4	1407	22.7	.59	1.60	.27	5.19	14.104125
~~B~~	~~0~~	~~100~~	~~KL~~	~~30~~	~~17.3~~	~~16.4~~	~~636.8~~	~~73.0~~	~~10.4~~	~~1318~~	~~25.7~~	~~.50~~	~~6.41~~	~~.72~~	~~4.24~~	~~14.241392~~
A	0	100	KL	20	16.7	16.3	614.7	62.4	6.4	1408	22.7	.59	4.54	.29	5.19	15.017611
B	0	100	KL	20	16.9	16.5	633.5	71.0	5.6	1365	25.2	.53	4.60	.33	5.18	15.107819
~~A~~	~~1~~	~~100~~	~~KL~~	~~20~~	~~17.5~~	~~17.1~~	~~608.0~~	~~62.4~~	~~2.8~~	~~1379~~	~~21.8~~	~~.56~~	~~1.54~~	~~.26~~	~~5.68~~	~~15.287980~~
B	1	100	KL	20	17.3	17.1	645.4	72.0	3.5	1356	25.0	.52	1.58	.09	5.88	15.384218
A	1	100	KL	30	14.8	14.7	568.2	73.2	9.2	1375	22.5	.52	2.17	.39	5.54	15.439455
~~B~~	~~1~~	~~100~~	~~KL~~	~~30~~	~~18.2~~	~~17.0~~	~~675.9~~	~~76.8~~	~~6.5~~	~~1308~~	~~26.1~~	~~.48~~	~~1.80~~	~~.21~~	~~5.97~~	~~15.966607~~
B	0	100	KL	20	17.3	17.0	645.4	72.0	3.5	1356	25.0	.52	4.49	.27	5.67	16.154125
A	1	100	KL	20	15.2	14.9	607.1	72.0	4.9	1426	22.6	.55	1.80	.51	5.79	16.248314
~~A~~	~~0~~	~~100~~	~~KL~~	~~20~~	~~17.6~~	~~17.1~~	~~608.0~~	~~62.4~~	~~2.8~~	~~1379~~	~~21.9~~	~~.55~~	~~3.93~~	~~.31~~	~~5.87~~	~~16.586980~~
B	0	100	KL	30	15.4	14.7	552.7	69.1	12.7	1342	23.7	.52	19.97	1.49	2.99	16.982676

~~214 RECORDS~~

Appendix Q

EMISSIONS VERSUS SPEED FOR MINIMUM TWE AT FOUR VALUES OF PERCENT POWER

From the engine emissions data supplied by PRC, the points of minimum total weighted emissions were determined. These points were at 10, 25, 50, and 90 percent power at speeds of 1,200, 1,600, and 2,400 rpm. The first step in constructing emissions contours (i.e., emissions versus percent power and speed) for each of the constituents – HC, CO, and NO_x – and for total weighted emissions for the case of minimum total weighted emissions, was to construct curves of emissions versus speed for each percent power. Each curve was established by computer-aided curve fitting to give the perfect-fit binomial. These curves are as shown on the following pages.

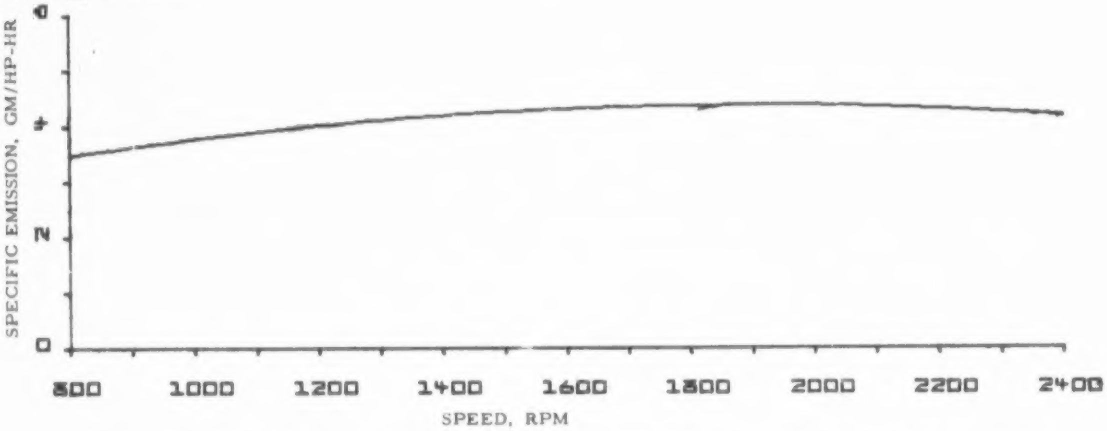


Fig. Q-1 CO Vs. RPM at 10-Percent Power for Minimum TWE – Engine A

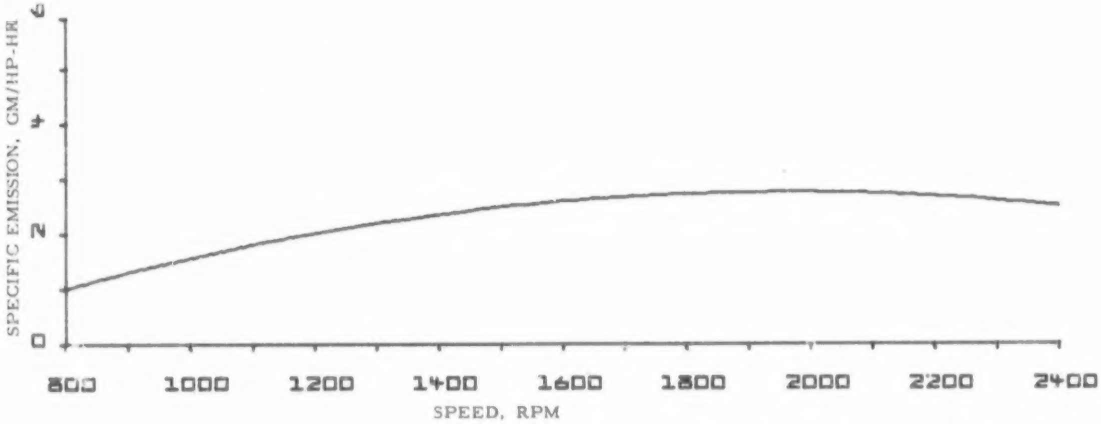


Fig. Q-2 CO Vs. RPM at 25-Percent Power for Minimum TWE – Engine A

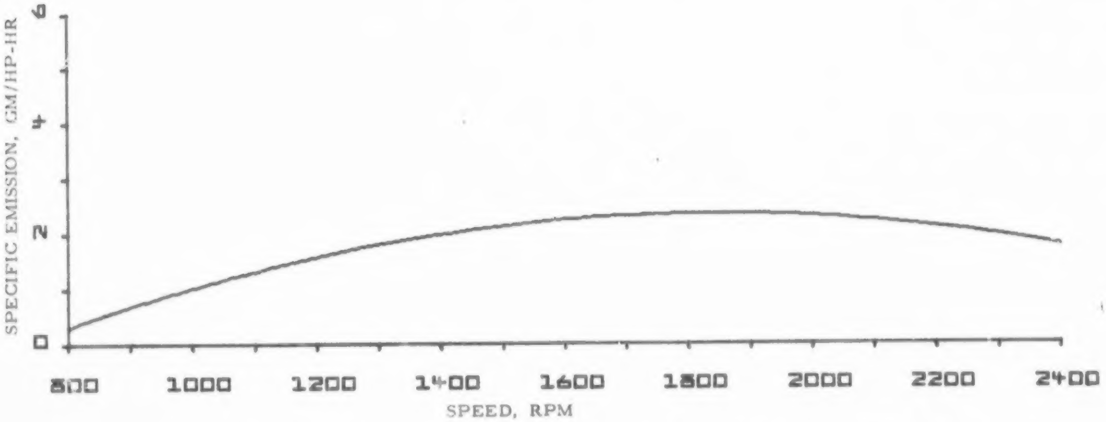


Fig. Q-3 CO Vs. RPM at 50-Percent Power for Minimum TWE – Engine A

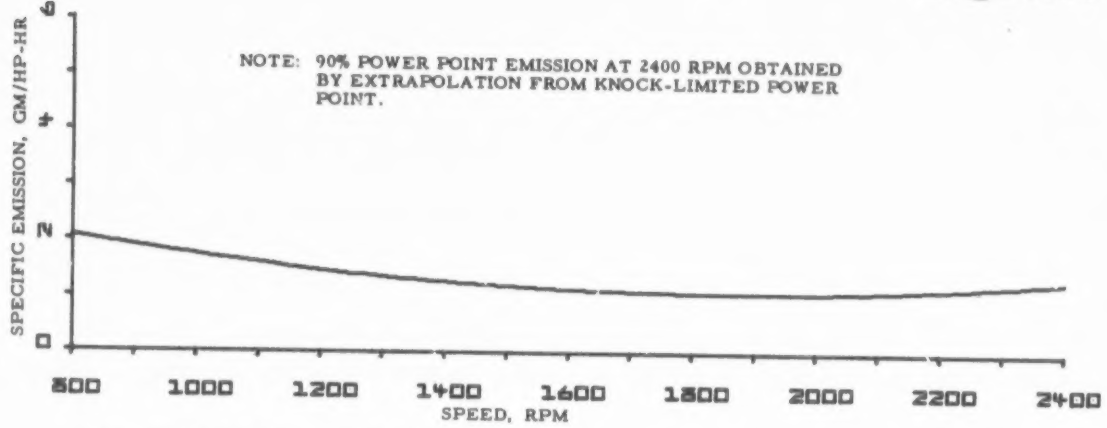


Fig. Q-4 CO Vs. RPM at 90-Percent Power for Minimum TWE – Engine A

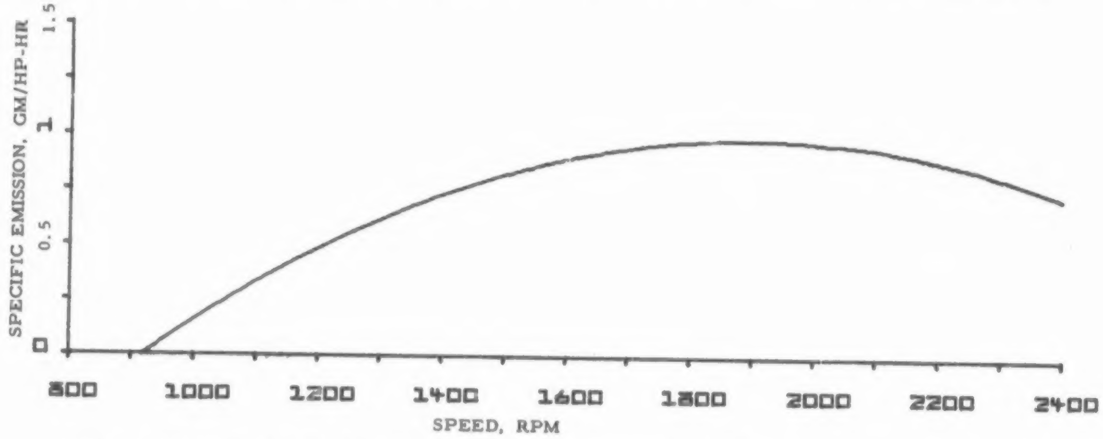


Fig. Q-5 HC Vs. RPM at 10-Percent Power for Minimum TWE – Engine A

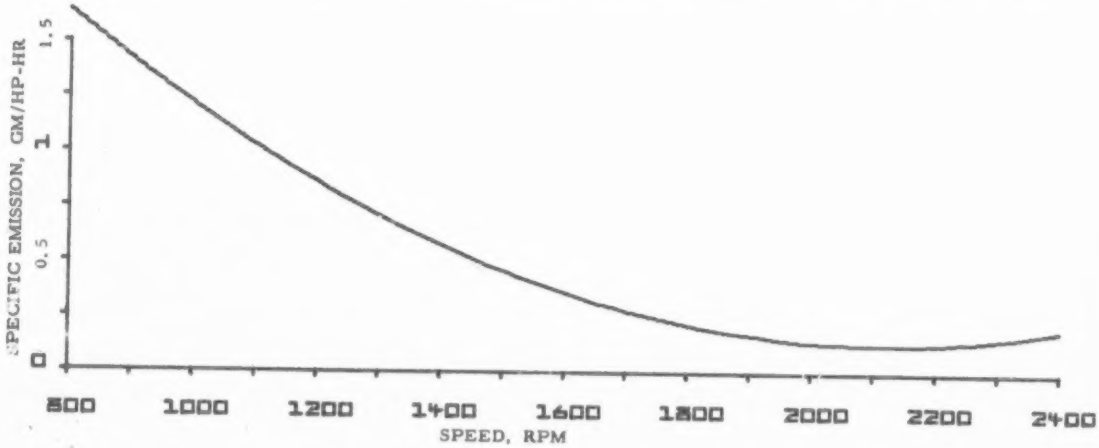


Fig. Q-6 HC Vs. RPM at 25-Percent Power for Minimum TWE – Engine A

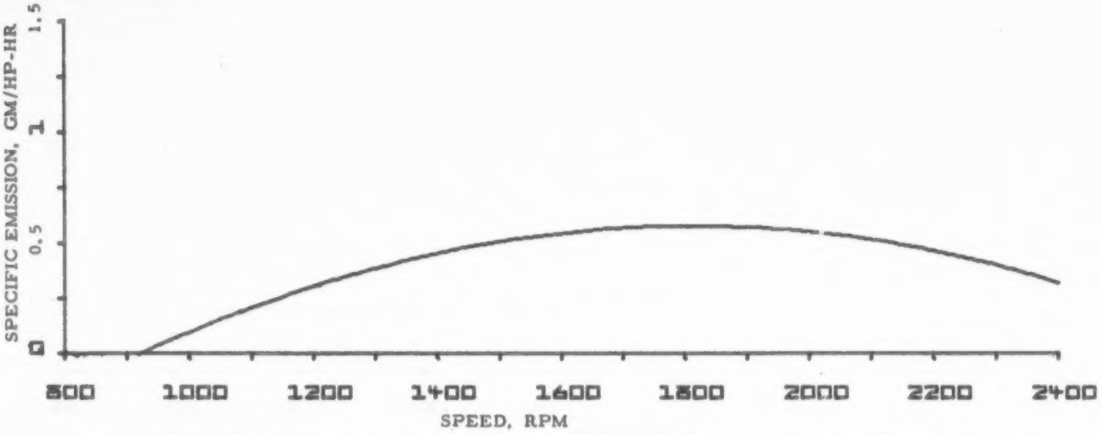
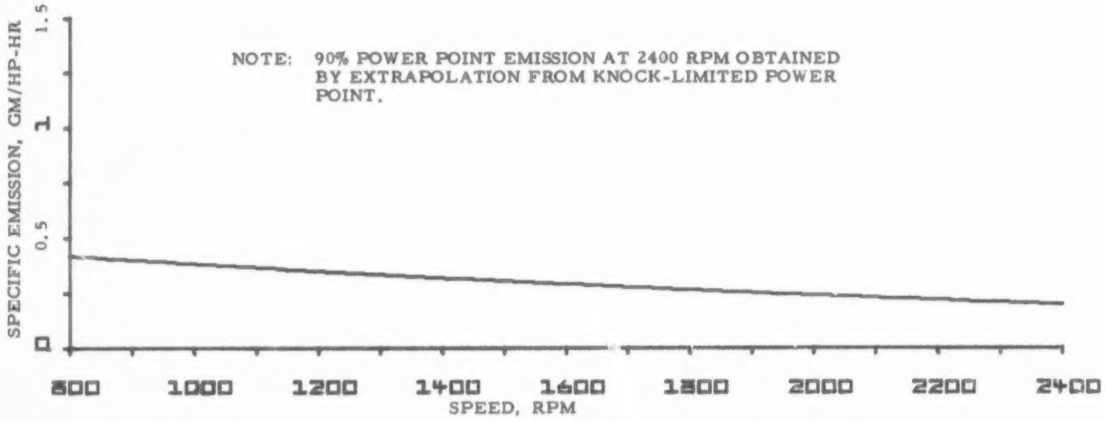


Fig. Q-7 HC Vs. RPM at 50-Percent Power for Minimum TWE -- Engine A



NOTE: 90% POWER POINT EMISSION AT 2400 RPM OBTAINED BY EXTRAPOLATION FROM KNOCK-LIMITED POWER POINT.

Fig. Q-8 HC Vs. RPM at 90-Percent Power for Minimum TWE – Engine A

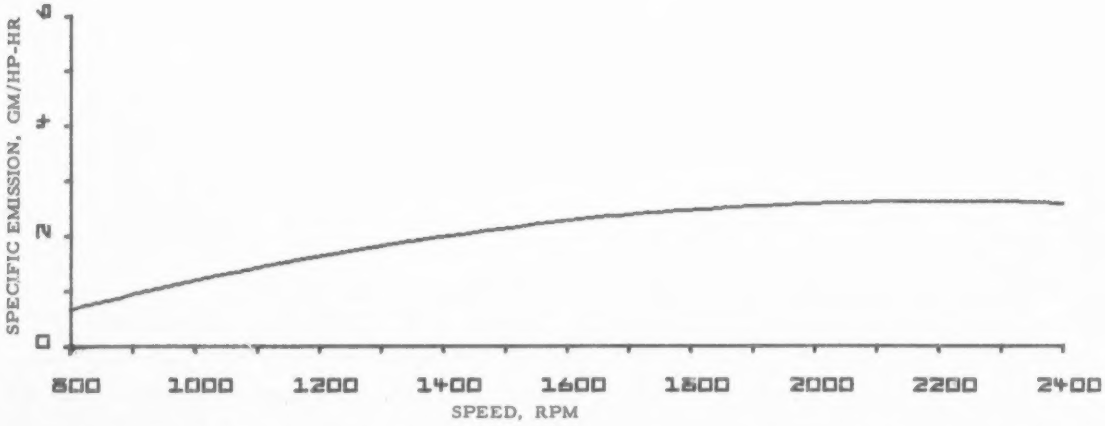


Fig. Q-9 NO_x Vs. RPM at 10-Percent Power for Minimum TWE – Engine A

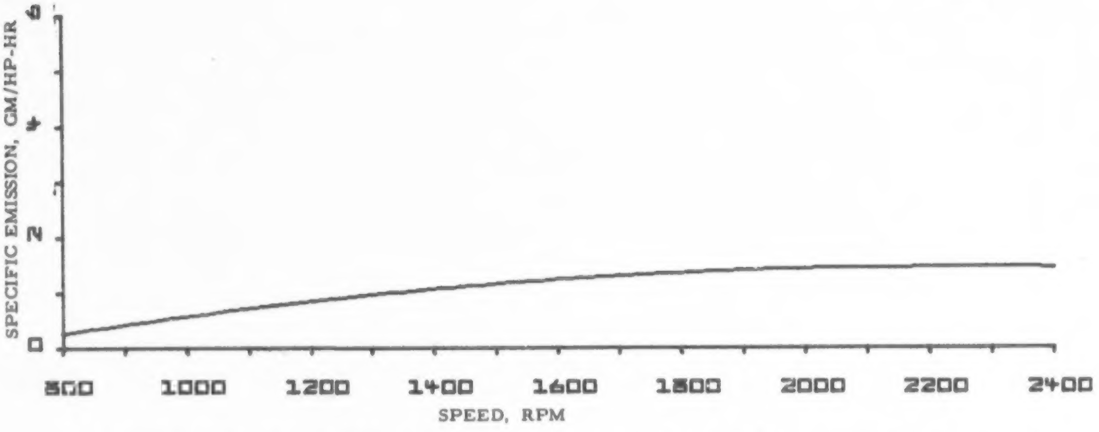


Fig. Q-10 NO_x Vs. RPM at 25-Percent Power for Minimum TWE – Engine A

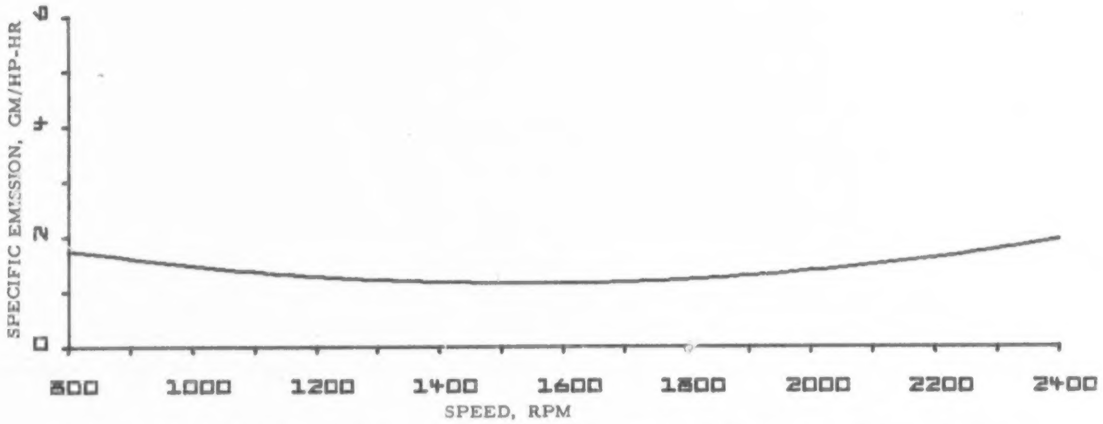
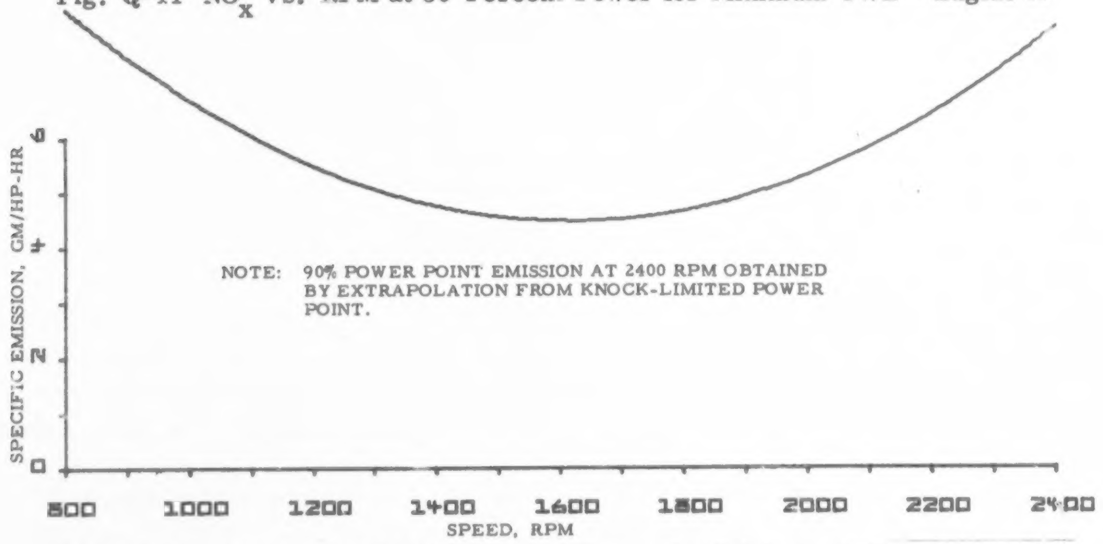


Fig. Q-11 NO_x Vs. RPM at 50-Percent Power for Minimum TWE – Engine A



NOTE: 90% POWER POINT EMISSION AT 2400 RPM OBTAINED BY EXTRAPOLATION FROM KNOCK-LIMITED POWER POINT.

Fig. Q-12 NO_x Vs. RPM at 90-Percent Power for Minimum TWE – Engine A

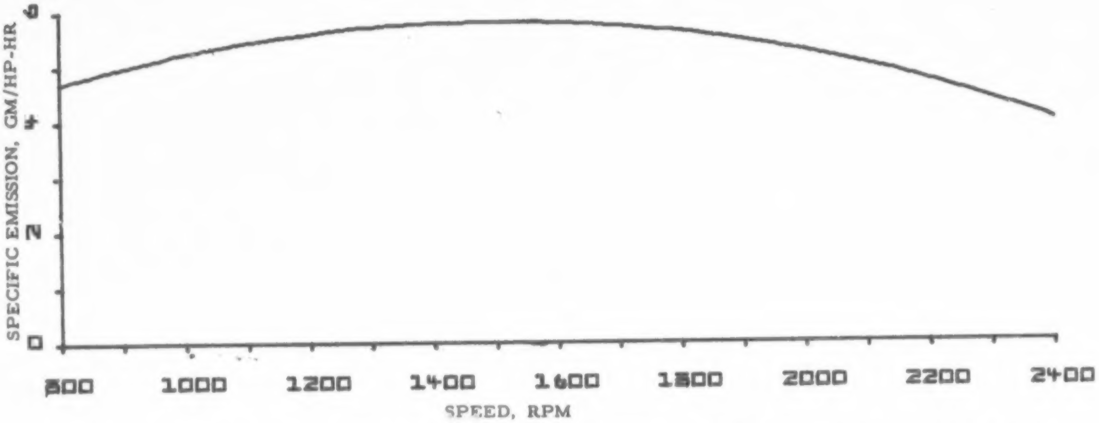


Fig. Q-13 CO Vs. RPM at 10-Percent Power for Minimum TWE – Engine B

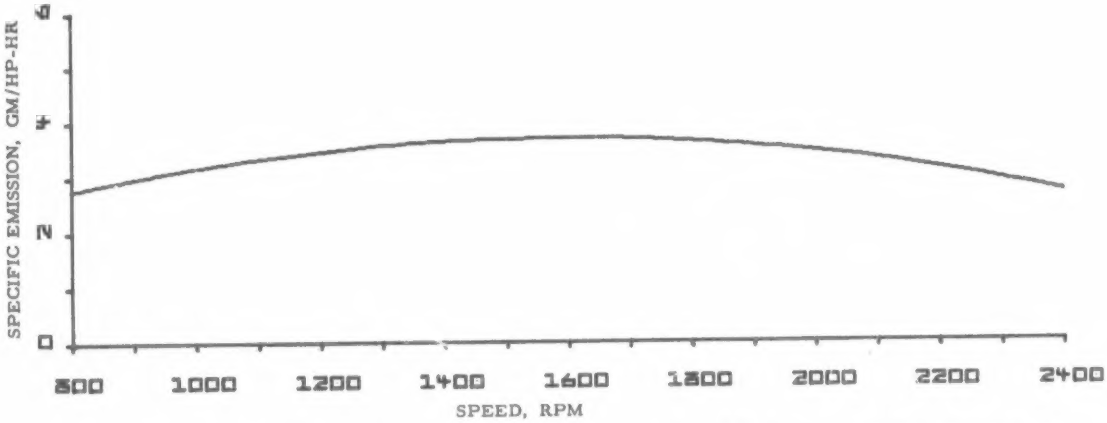


Fig. Q-14 CO Vs. RPM at 25-Percent Power for Minimum TWE – Engine B

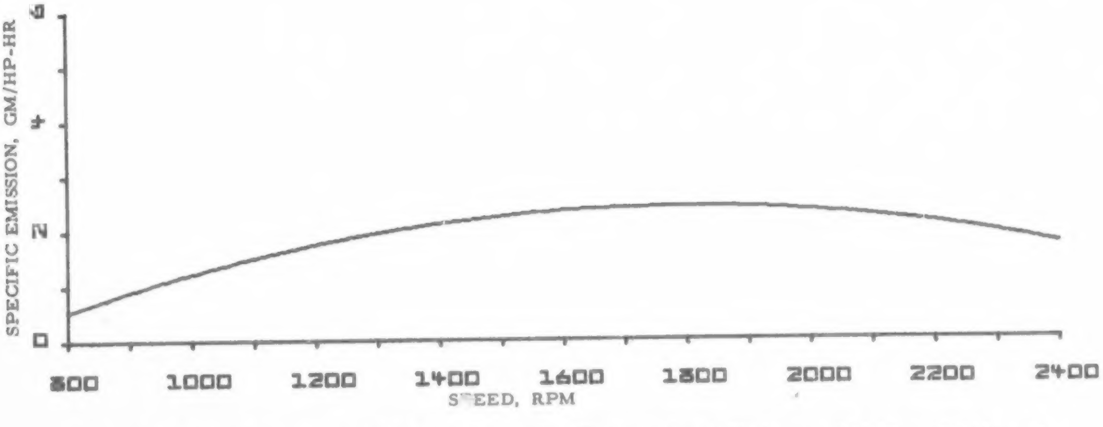


Fig. Q-15 CO Vs. RPM at 50-Percent Power for Minimum TWE – Engine B

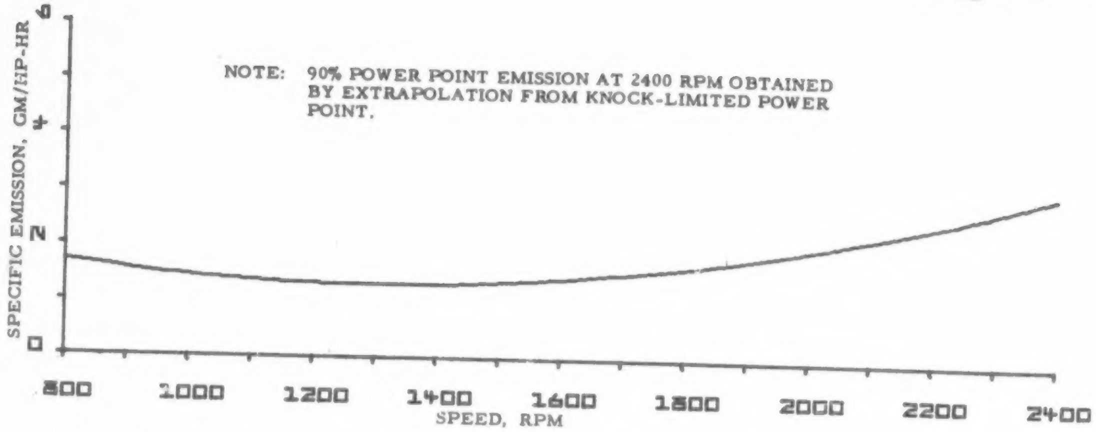


Fig. Q-16 CO Vs. RPM at 90-Percent Power for Minimum TWE – Engine B

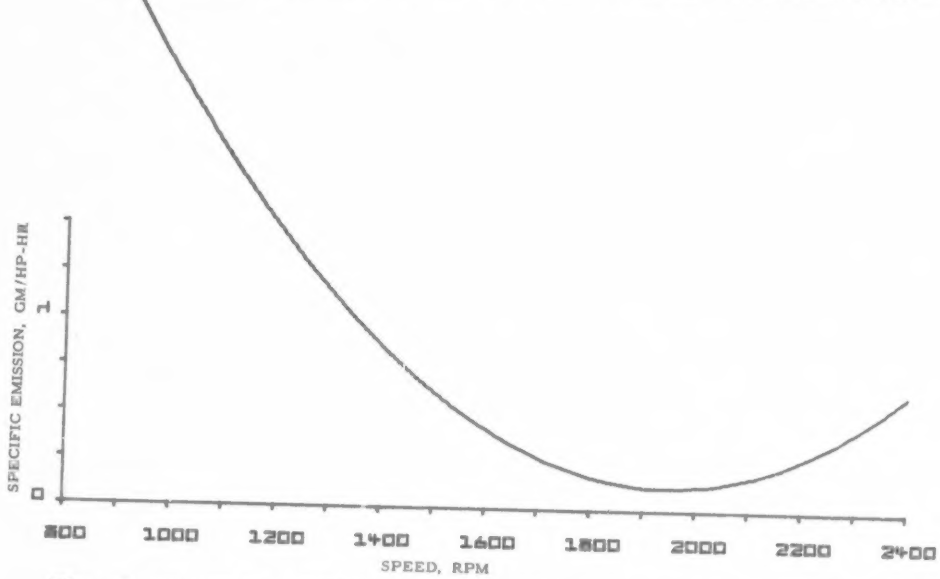


Fig. Q-17 HC Vs. RPM at 10-Percent Power for Minimum TWE – Engine B

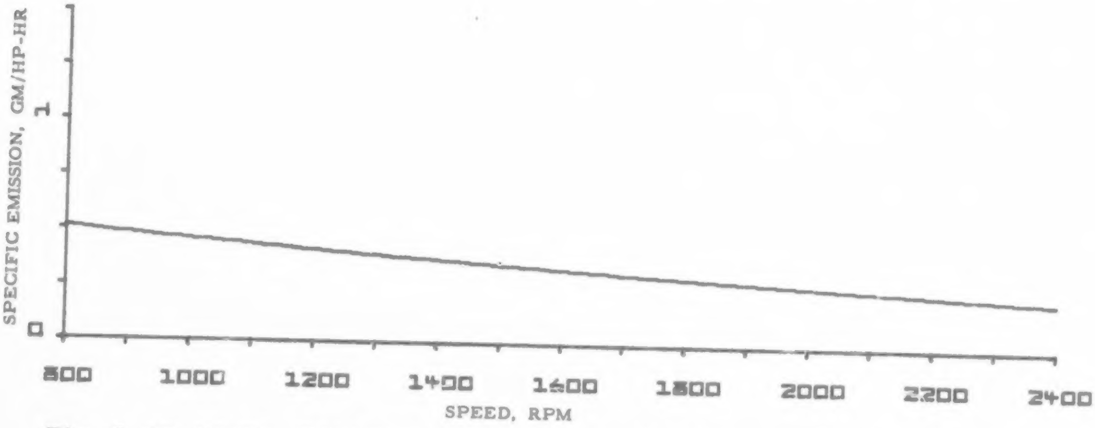


Fig. Q-18 HC Vs. RPM at 25-Percent Power for Minimum TWE – Engine B

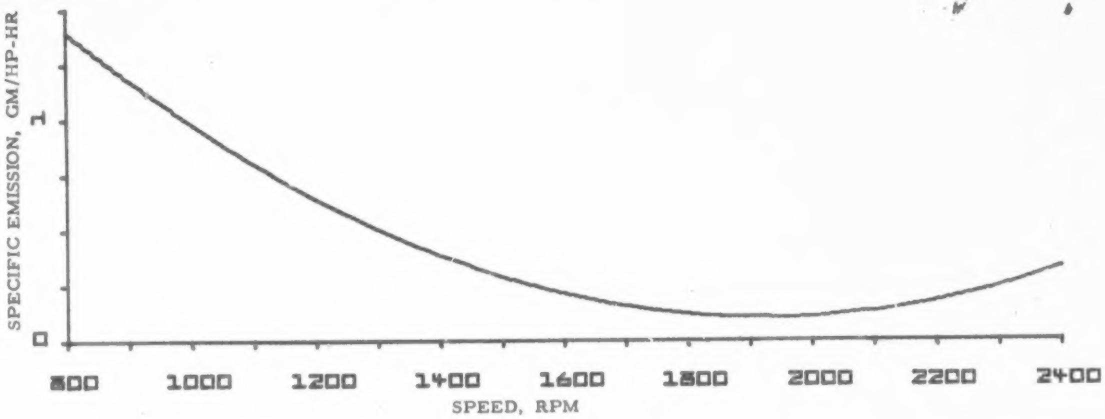
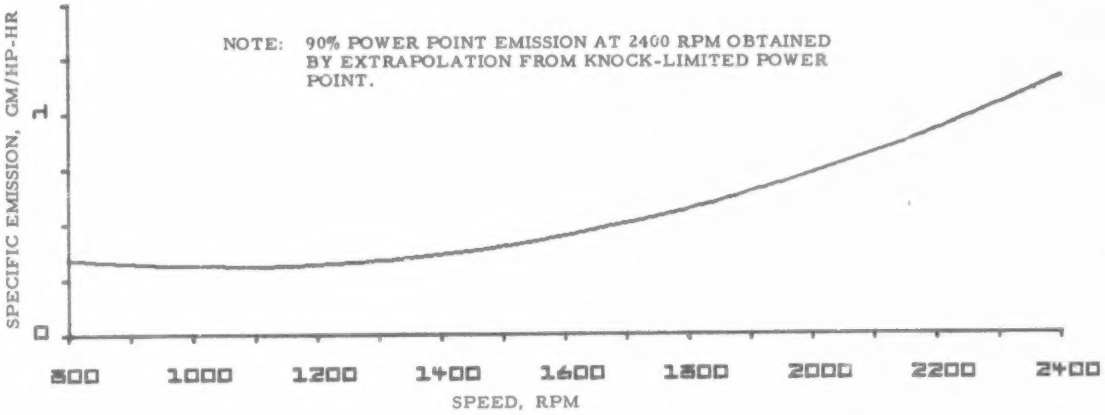


Fig. Q-19 HC Vs. RPM at 50-Percent Power for Minimum TWE – Engine B



NOTE: 90% POWER POINT EMISSION AT 2400 RPM OBTAINED BY EXTRAPOLATION FROM KNOCK-LIMITED POWER POINT.

Fig. Q-20 HC Vs. RPM at 90-Percent Power for Minimum TWE – Engine B

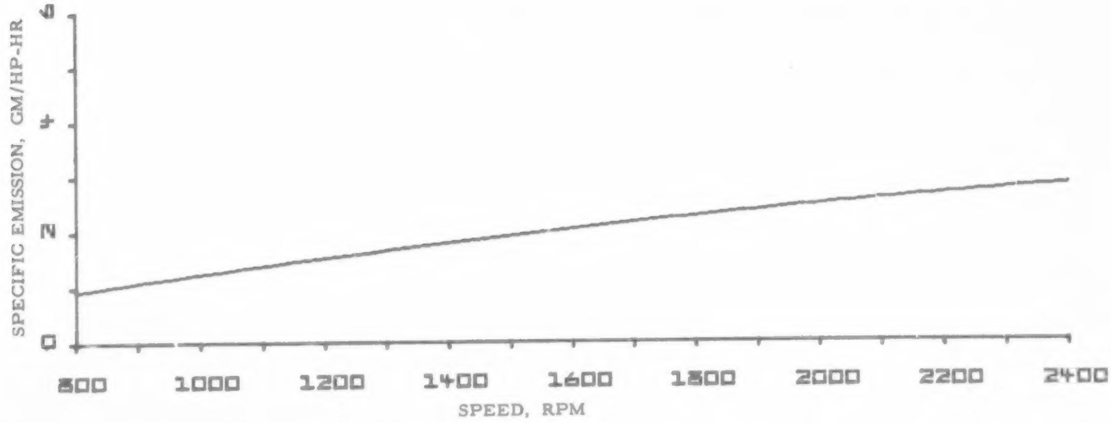


Fig. Q-21 NO_x Vs. RPM at 10-Percent Power for Minimum TWE – Engine B

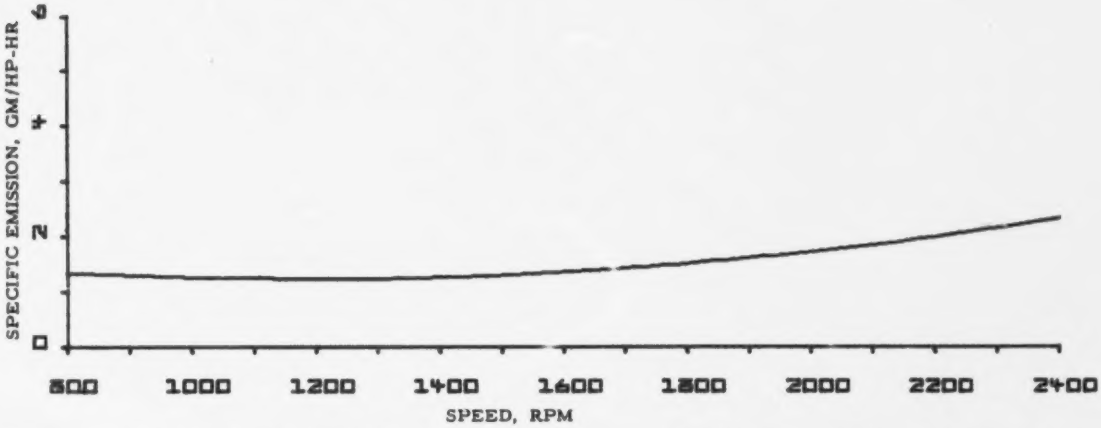


Fig. Q-22 NO_x Vs. RPM at 25-Percent Power for Minimum TWE – Engine B

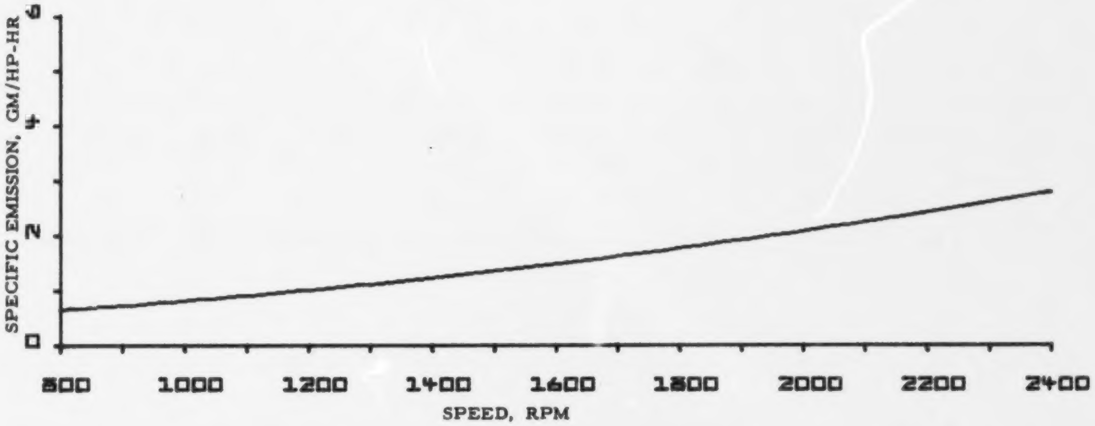


Fig. Q-23 NO_x Vs. RPM at 50-Percent Power for Minimum TWE – Engine B

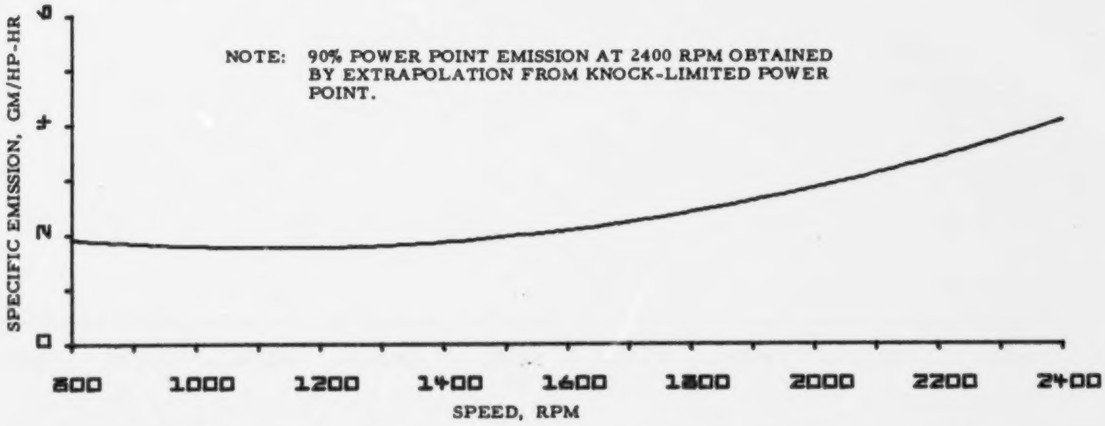

NOTE: 90% POWER POINT EMISSION AT 2400 RPM OBTAINED BY EXTRAPOLATION FROM KNOCK-LIMITED POWER POINT.

Fig. Q-24 NO_x Vs. RPM at 90-Percent Power for Minimum TWE – Engine B

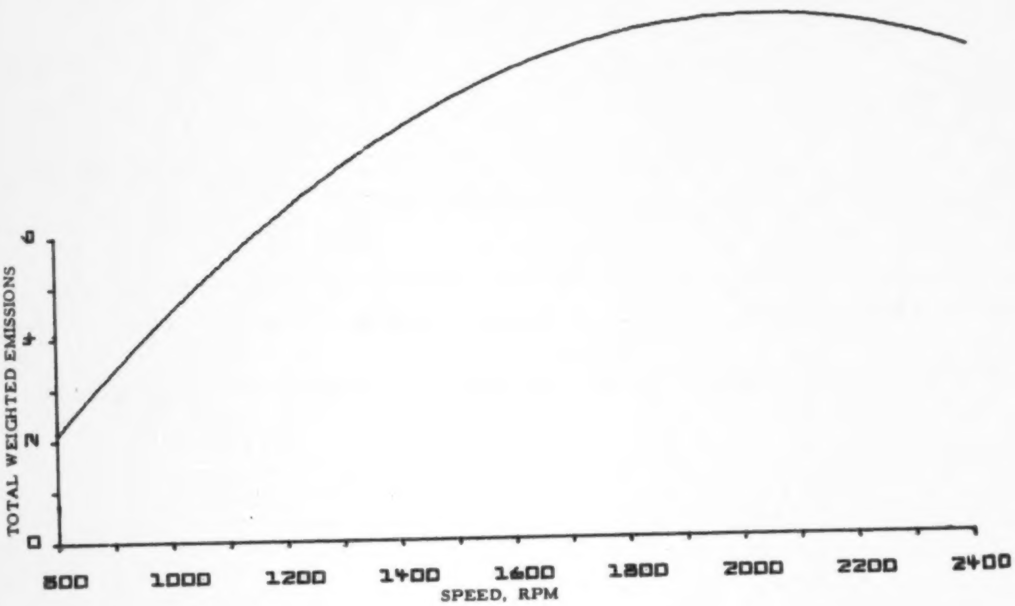


Fig. Q-25 TWE Vs. RPM at 10-Percent Power for Minimum TWE – Engine A

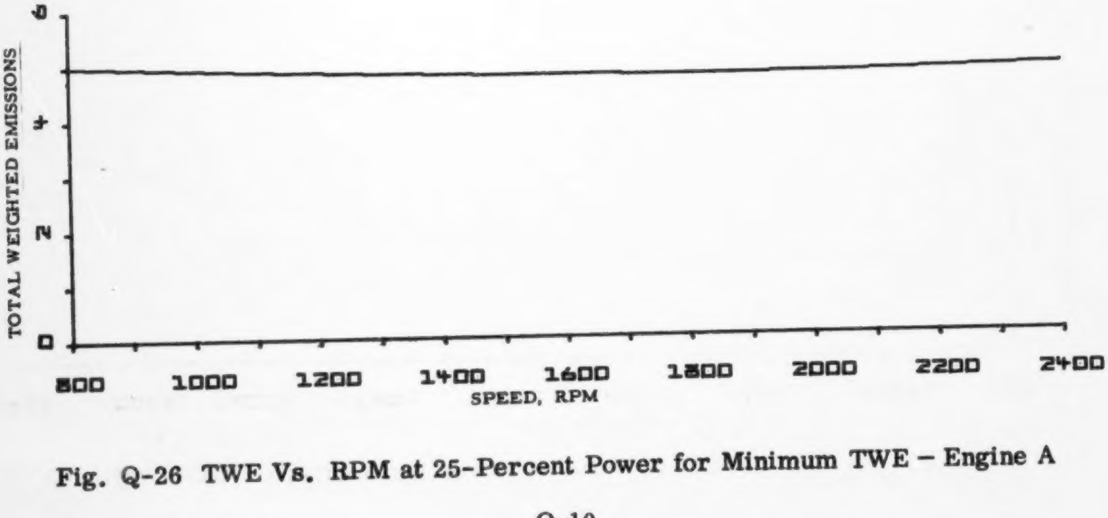


Fig. Q-26 TWE Vs. RPM at 25-Percent Power for Minimum TWE – Engine A

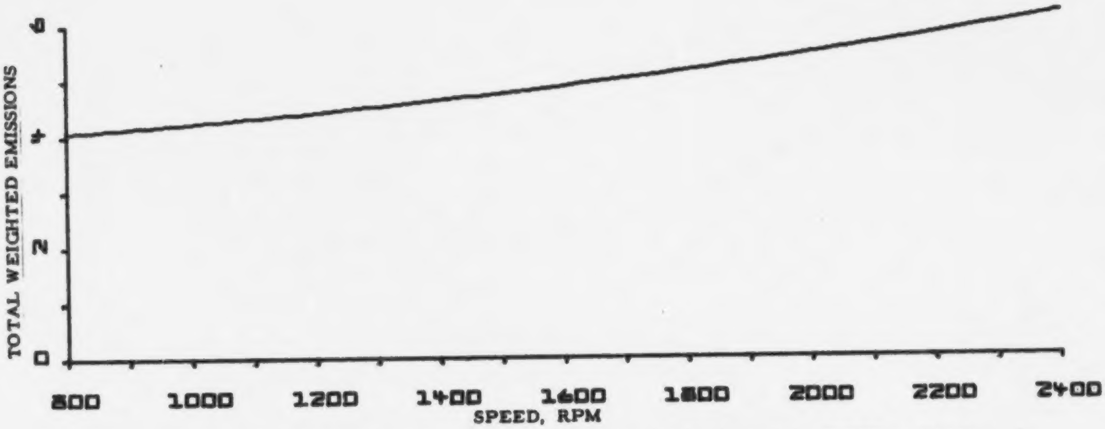
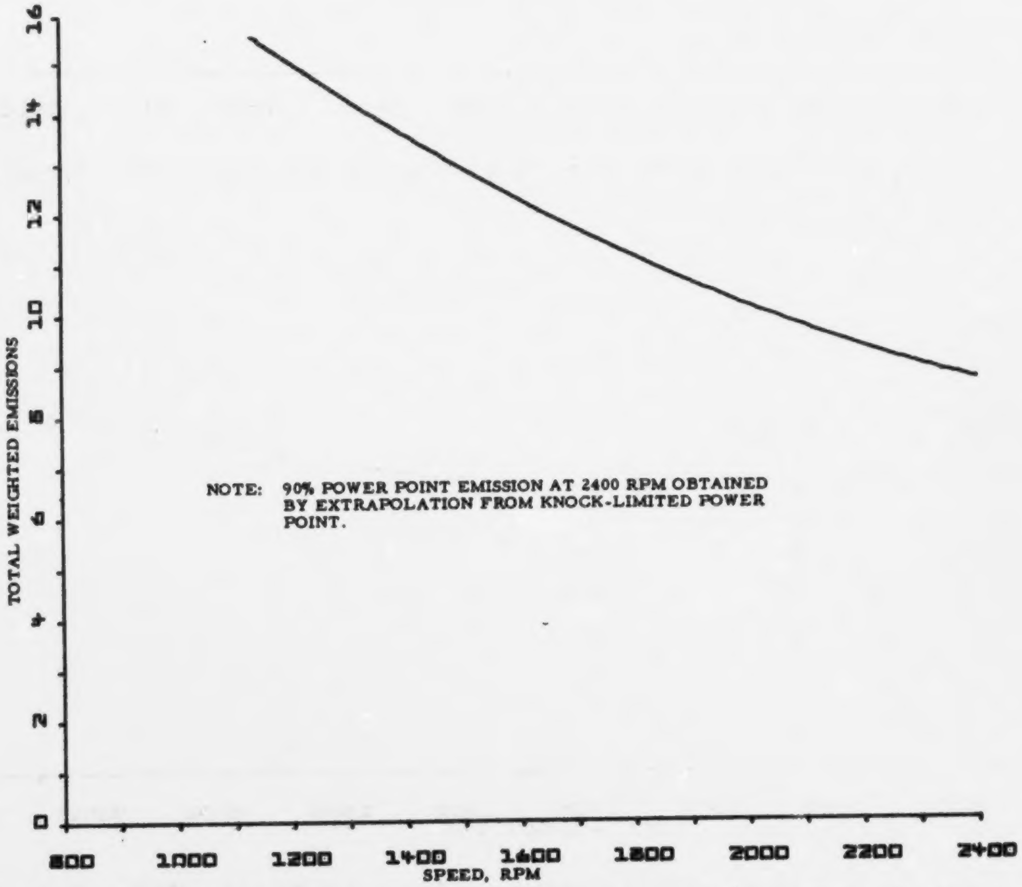


Fig. Q-27 TWE Vs. RPM at 50-Percent Power for Minimum TWE – Engine A



NOTE: 90% POWER POINT EMISSION AT 2400 RPM OBTAINED BY EXTRAPOLATION FROM KNOCK-LIMITED POWER POINT.

Fig. Q-28 TWE Vs. RPM at 90-Percent Power for Minimum TWE – Engine A

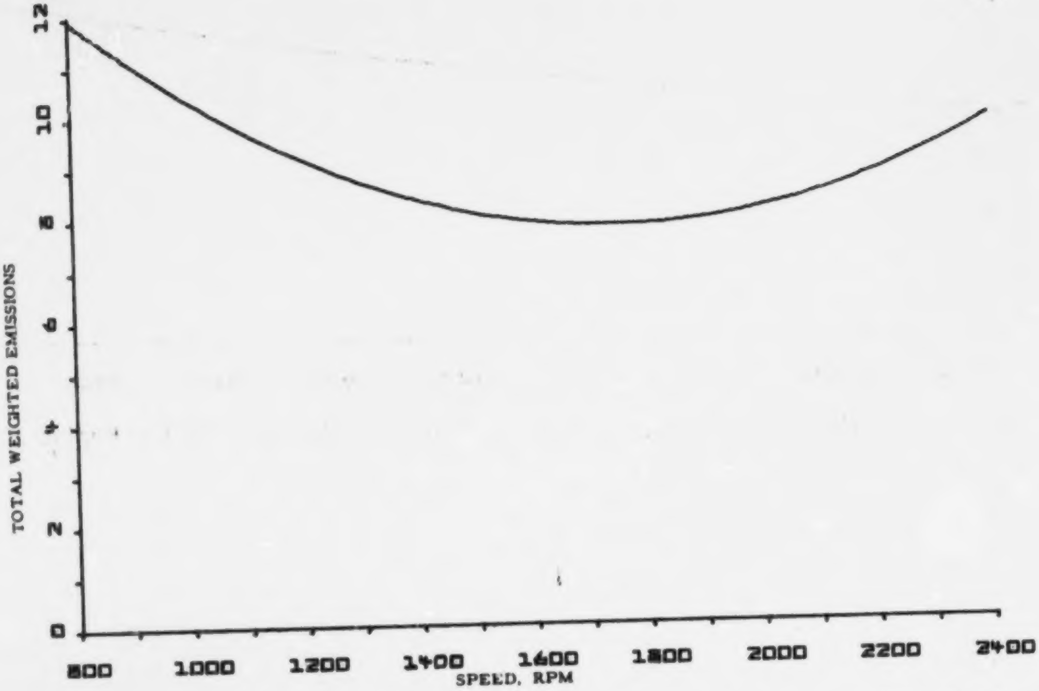


Fig. Q-29 TWE Vs. RPM at 10-Percent Power for Minimum TWE – Engine B

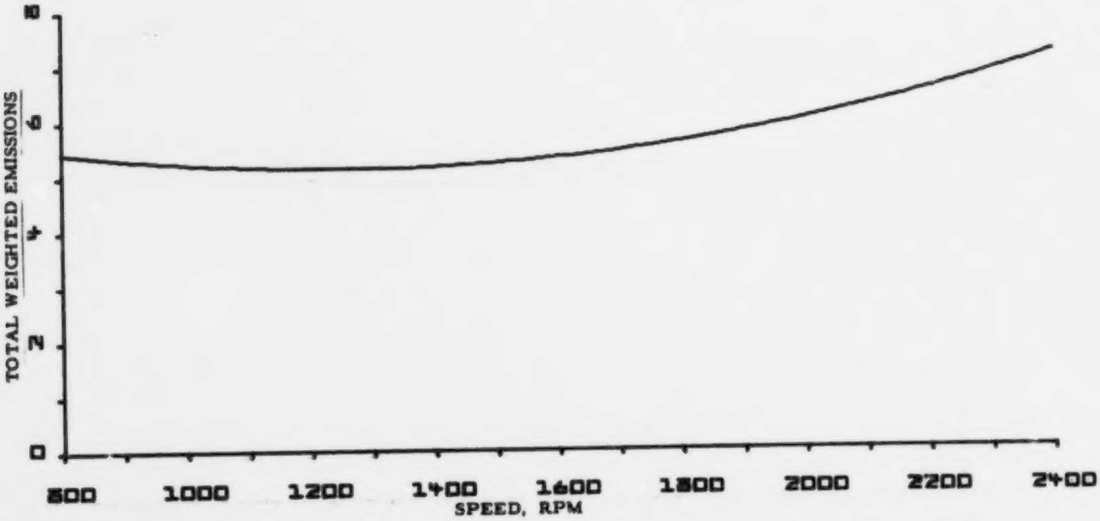


Fig. Q-30 TWE Vs. RPM at 25-Percent Power for Minimum TWE – Engine B

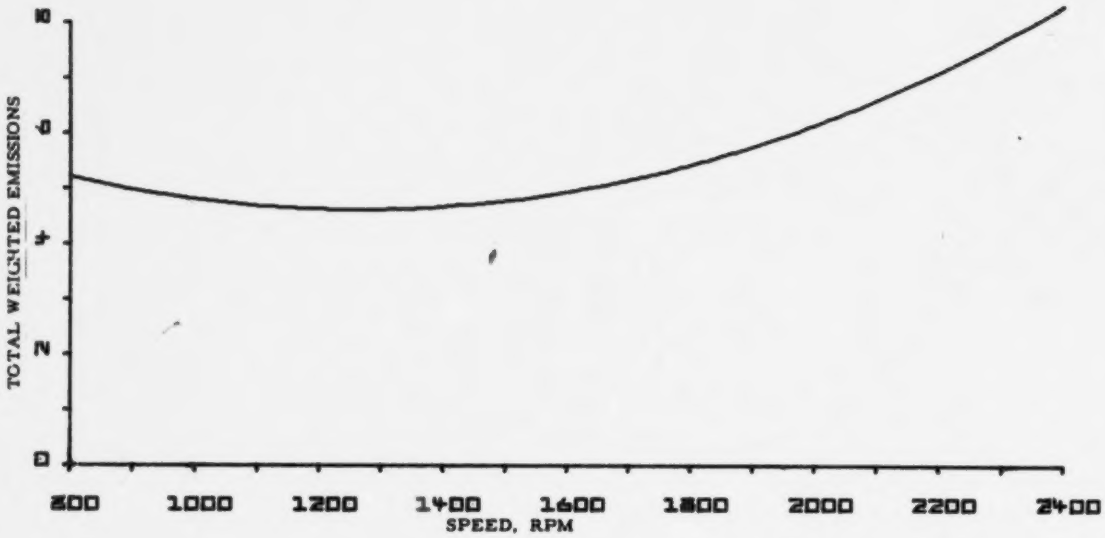
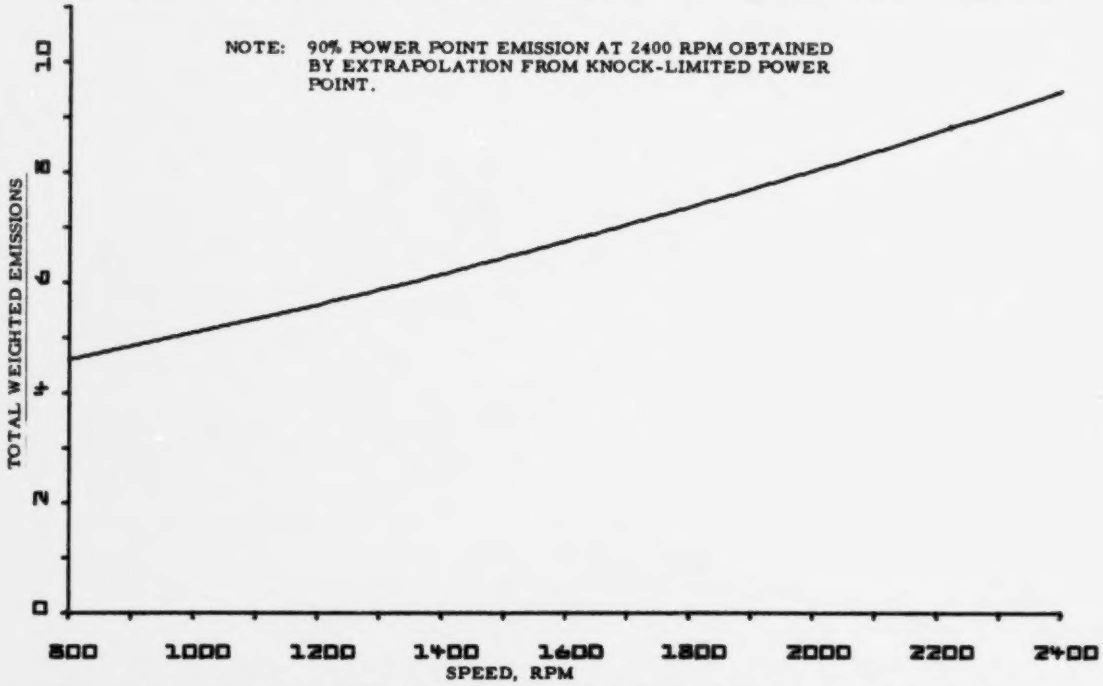


Fig. Q-31 TWE Vs. RPM at 50-Percent Power for Minimum TWE – Engine B



NOTE: 90% POWER POINT EMISSION AT 2400 RPM OBTAINED BY EXTRAPOLATION FROM KNOCK-LIMITED POWER POINT.

Fig. Q-32 TWE Vs. RPM at 90-Percent Power for Minimum TWE – Engine B